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# Real-Time Electroencephalogram Sonification for Neurofeedback

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Submitted for the degree of Doctor of Philosophy in

Department of Computing and Communications

The Open University

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## Abstract

Electroencephalography (EEG) is the measurement via the scalp of the electrical activity of the brain. The established therapeutic intervention of neurofeedback involves presenting people with their own EEG in real-time to enable them to modify their EEG for purposes of improving performance or health.

The aim of this research is to develop and validate real-time sonifications of EEG for use in neurofeedback and methods for assessing such sonifications. Neurofeedback generally uses a visual display. Where auditory feedback is used, it is mostly limited to pre-recorded sounds triggered by the EEG activity crossing a threshold. However, EEG generates time-series data with meaningful detail at fine temporal resolution and with complex temporal dynamics. Human hearing has a much higher temporal resolution than human vision, and auditory displays do not require people to focus on a screen with their eyes open for extended periods of time – e.g. if they are engaged in some other task. Sonification of EEG could allow more rapid, contingent, salient and temporally detailed feedback. This could improve the efficiency of neurofeedback training and reduce the number and duration of sessions for successful neurofeedback.

The same two deliberately simple sonification techniques were used in all three experiments of this research: Amplitude Modulation (AM) sonification, which maps the fluctuations in the power of the EEG to the volume of a pure tone; and Frequency Modulation (FM) sonification, which uses the changes in the EEG power to modify the frequency. Measures included, a listening task, NASA task load index; a measure of how much work it was to do the task, Pre & post measures of mood, and EEG.

The first experiment used pre-recorded single channel EEG and participants were asked to listen to the sound of the sonified EEG and try and track the activity that they could hear by moving a slider on a computer screen using a computer mouse. This provided a quantitative assessment of how well people could perceive the sonified fluctuations in EEG level. The tracking accuracy

scores were higher for the FM sonification but self-assessments of task load rated the AM sonification as easier to track.

The second experiment used the same two sonifications, in a real neurofeedback task using participants own live EEG. Unbeknownst to the participants the neurofeedback task was designed to improve mood. A Pre-Post questionnaire showed that participants changed their self-rated mood in the intended direction with the EEG training, but there was no statistically significant change in EEG. Again the FM sonification showed a better performance but AM was rated as less effortful. The performance of sonifications in the tracking task in experiment 1 was found to predict their relative efficacy at blind self-rated mood modification in experiment 2.

The third experiment used both the tracking as in experiment 1 and neurofeedback tasks as in experiment 2, but with modified versions of the AM and FM sonifications to allow two-channel EEG sonifications. This experiment introduced a physical slider as opposed to a mouse for the tracking task. Tracking accuracy increased, but this time no significant difference was found between the two sonification techniques on the tracking task. In the training task, once more the blind self-rated mood did improve in the intended direction with the EEG training, but as again there was no significant change in EEG, this cannot necessarily be attributed to the neurofeedback. There was only a slight difference between the two sonification techniques in the effort measure.

In this way, a prototype method has been devised and validated for the quantitative assessment of real-time EEG sonifications. Conventional evaluations of neurofeedback techniques are expensive and time consuming. By contrast, this method potentially provides a rapid, objective and efficient method for evaluating the suitability of candidate sonifications for EEG neurofeedback.

## Acknowledgments

First of all, I would like to thank all of the people who volunteered to take part in my experiments. Without their time and commitment this research could not have happened.

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I am also most grateful and tänama for the assistance, support, advice and guidance of my long-time collaborator and co-author Associate Professor Dr Aleksander Väljamäe at the Human Computer Interaction group, Tallinn University, Estonia.

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## Declaration

I hereby declare that I conducted the research presented in this dissertation.

I collaborated with my co-authors; Dr Aleksander Valjamae, Sebastian Mealla, Dr Sergi Jordà, Aluizio Oliveira, Xavier Marimon, and Dr Raul Benitez, on a conference paper called "A review of real-time EEG sonification research", that came out of my literature review and some of this material appears in the literature survey of this dissertation.

I also received some assistance on statistical analysis, Matlab and research design from my co-author, Dr Aleksander Valjamae, on a conference paper called "Prototyping A Method for the Assessment of Real-Time EEG Sonifications" about the first of my three experiments.

## Publications

Some of the research in this dissertation has also been published in the following:

Väljamäe, A.; Steffert, T.; Mealla, S.; Holland, S.; Marimon, X.; Benitez, R.; Oliveira, A. and Jordà, S. (2013). **A review of real-time EEG sonification research**. In: International Conference on Auditory Display 2013 (ICAD 2013), 6-10 July 2013, Lodz, Poland.

Steffert, Tony; Holland, Simon; Mulholland, Paul; Dalton, Sheep and Väljamäe, Aleksander (2015). **Prototyping a method for the assessment of real-time EEG sonifications**. In: 21st International Conference on Auditory Display, 8-10 July 2015, Graz, Austria. (**Winner of the best student paper**)

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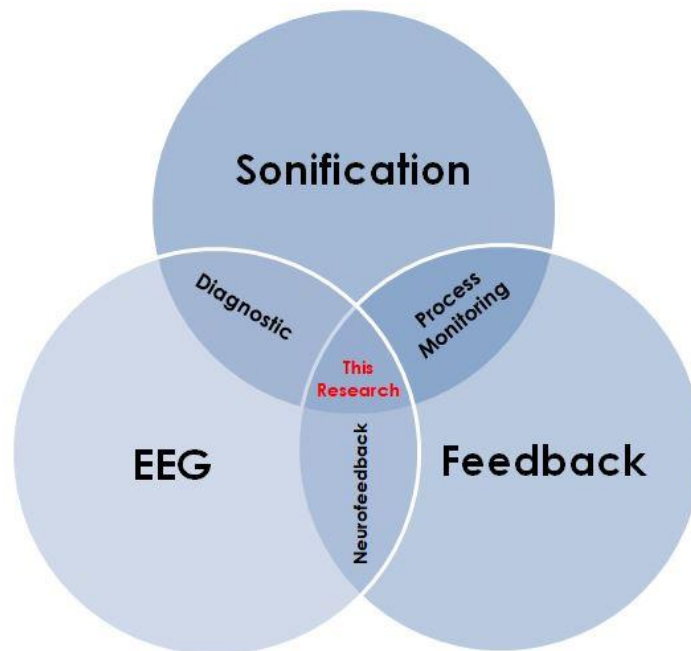
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## Chapter 1: Introduction

Depicted in figure 1.1, this research explores the intersection of three different domains; Electroencephalography, Neurofeedback and Sonification.



**Figure 1.1:** Venn diagram of the three intersecting research domains of sonification, EEG and feedback that this research exists within.

**Electroencephalography** (EEG) is the measurement from the scalp of the electrical activity of the brain; it is a rich and complex source of multivariate time-series data that can reveal information about the cognitive, motor, sensory and emotional events of the brain (Kropotov, 2010).

**Neurofeedback** is a therapeutic intervention that presents a person with their real-time EEG in order to enable them to learn how to control and modify their own physiological activity and concomitant mental state in order to improve health or performance (Sterman, 2000).

**Sonification** is the process of converting complex data into sound to convey the data and data relationships (Kramer et al., 1999, p. 2).

The real-time presentation of EEG data with sonification offers a number of potential advantages for neurofeedback. The principal goal for this research is to develop and validate sonifications that are specifically appropriate for the real-time display of EEG for neurofeedback. Thus the primary research question is:

**How can real-time electroencephalogram data be sonified to support neurofeedback?**

This chapter will give a brief review of these three intersecting disciplines that underpin this research and that provide the motivation. It will then set out the Research design and the structure of the dissertation.

## 1.1. Background

### 1.1.1. Electroencephalography

The **human brain** has around 86 billion neurons (Herculano-Houzel, 2009), with each neuron being connected to between one thousand and ten thousand other neurons (Ward, 2010). Information is passed between neurons by tiny “spikes” of electricity called **action potentials** that last less than a thousandth of a second. “The action potential is considered as the simplest event of information processing in a neuronal network” (Kropotov, 2010). A neuron can

have a firing rate of between 100 to 1000 spikes per second (Kropotov, 2010). This gives the potential of 8 quadrillion action potentials per second in a human brain. It is the rate of firing of a neuron, rather than the amplitude of the firing, that encodes information (Recce, 1998).

**Electroencephalography (EEG)** is a safe and **non-invasive** (Burle et al., 2015) method of measuring the summation of thousands of action potentials from the scalp. EEG is a functional measure of neuronal activity and can give information about cognitive, motor, sensory and emotional states and events. EEG has a high temporal resolution in comparison to other new imaging techniques, with a typical EEG system having a sample rate of 500 Hz, giving a data point every 2 milliseconds (ms) (Kropotov, 2010). In comparison, functional magnetic resonance imaging (fMRI) can have a temporal resolution of 500 ms, but the blood-flow response that it measures evolves over many seconds (Kropotov, 2010). EEG equipment has the further advantage over many competing brain imaging methods that it is substantially cheaper, with EEG systems costing from a few hundred pounds up to thousands of pounds. By contrast, an fMRI system can cost millions of pounds. Also, unlike other neuroimaging techniques, EEG equipment can be small, light and portable. This means EEG is a cheap non-invasive, safe and convenient method for measuring mental activity with high temporal resolution that can easily be used outside of the lab.

EEG has both real-time and offline applications. **Off-line EEG** is an established **diagnostic** tool for identifying functional disturbances in brain activity that are typically indicative of conditions such as epilepsy, coma, brain death, sleep stages and sleep disorders (See [2.1.2. Electroencephalography and](#)

quantitative EEG). In addition, the emerging field of **quantitative EEG** (qEEG) i.e. EEG which is systematically analysed with the aid of new statistical techniques and normative databases, has over the last few decades greatly expanded the utility and diagnostic range of EEG to include areas such as Attention Deficit Hyperactivity Disorder (ADHD), Schizophrenia, Addiction, Obsessive-Compulsive Disorder, Depression and Alzheimer's (Kropotov, 2010).

**Real-time** EEG has three main application areas. First, **Brain-Computer Interface** (BCI) (Curran, 2003), is used to help paralysed people to communicate with external devices such as text-to-speech software or to control hardware such as an electric wheelchair. The second application area is continuous **EEG Monitoring** used in intensive care units and emergency rooms for the surveillance of acute brain dysfunction and to detect abnormalities before they become irreversible (Jordan, 1999). The third broad sub-domain of real-time EEG is **Neurofeedback**,

**Section 2.1** will give a more in-depth summary of the historical, technical and physiological aspects of the Electroencephalography relevant for this research.

### 1.1.2. Neurofeedback

**Neurofeedback** is an established therapeutic learning intervention in use since the 1960s, in which a participant's own EEG parameters are presented back to them in real-time to facilitate the learning of control of their own physiology via this feedback loop. This enables people to learn how to change their physiological activity for the purpose of improving health and performance (Stermann, 2000).

Neurofeedback has been classified by a joint taskforce of the Association for Applied Psychophysiology and Biofeedback (AAPB) and the International Society for Neurofeedback & Research (ISNR) as "efficacious" or "efficacious and specific"<sup>1</sup> for several conditions (Yucha and Gilbert, 2004), including ADHD (Arns et al., 2009), and generalized anxiety disorder (Rice et al., 1993).

Neurofeedback has also been applied in other areas for which clinical evidence is not so well established yet, such as epilepsy (Sterman, 1972), dyslexia (Steffert and Steffert, 2014), sleep problems (Hoedlmoser et al., 2008), autism, headaches, anxiety, insomnia, substance abuse, pain disorders and traumatic brain injury (Thomas and Smith, 2015).

The feedback is typically given on a computer screen in the form of a histogram or line chart that reflects the amplitude of a given EEG frequency band, or in the form of a game-like display, where the EEG controls the behaviour or appearance of the game (Hammond, 2007). For example, if a person was able to sustain their concentration, this would typically be characterised by an increase in EEG Beta power (15 to 18 Hz), while Theta power (4 to 8 Hz) would typically decrease in the front of the brain. When the Beta and Theta crossed a pre-set amplitude threshold, a computer graphic of a rocket ship could be programmed to start to move, and the sound of the engines to play. If the participant's concentration waned, then the Beta would drop below the threshold and the rocket ship would stop.

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<sup>1</sup> The terms "efficacious" and "efficacious and specific" are terms for statistically evaluating therapeutic practice from an evidence-based standpoint.

In order to make a lasting change in symptoms or physiology neurofeedback typically requires between 10 and 40 training sessions, each of around 20 to 40 minutes (Hammond, 2007).

**Operant conditioning** (Skinner, 1938) is generally proposed as both the initial and primary mechanism for learning with neurofeedback (Hammond, 2007). Operant conditioning uses feedback and reward to modify voluntary behaviours. According to the theory of operant conditioning, there are three critical factors in determining how effective a reward will be in the conditioning **feedback loop**. The first is the **immediacy** of the feedback signal: the quicker the feedback, the shorter the learning time and the more rewarding the experience. Conversely, as the time between the behaviour and the reward is increased, known as "reinforcement delay", learning efficiency is decreased. The second factor is the **contingency** of the signal; this refers to how accurately or fully the signal represents the activity being trained. And finally **saliency** refers to how rewarding the reward is to the participant (Skinner, 1950).

Neurofeedback is generally considered to be based on two concepts. Firstly, the activity of the brain in both normal and abnormal functioning is objectively reflected in the EEG (Sterman, 1996; John et al., 1988). Secondly, Neuroplasticity of the brain allows behaviour to be modified by learning (Demarin et al., 2014).

Numerous studies from Pavlov (Pavlov, 1927) and Skinner (Skinner, 1953) have elucidated the mechanism referred to as conditioning and calculated how, when, and for how long, an animal or human can be induced to make a lasting change in behaviour. Both positive and negative conditioning have been codified into a reliable theory that is the basis of much psychology and

ethology (Gray, 1970). However in clinical settings usually only positive reward is used in neurofeedback in order to encourage aberrant EEG towards a more normal state (Kluetsch et al., 2014; Birbaumer et al., 2013).

Whilst over the last 45 years neurofeedback has had much success using visual and basic auditory displays as the feedback and reward mechanism, conditioning theory suggests that more immediate feedback, with closer contingency on brain activity and a more salient reward, would improve efficiency and reduce the number of sessions needed to make lasting brain changes, with implications for cost and time and the real-time sonification of EEG offers this possibility.

**Section 2.2** will outline conceptual underpinnings of neurofeedback relevant for this research.

### **1.1.3. Sonification**

Sonification is the systematic transformation of data into sound to facilitate the perception of that data (Kramer et al., 1999, P2.). In other words, sonification is a way of 'displaying' data using sound.

The human auditory system has evolved over millions of years to detect and track complex temporal auditory patterns embedded in complex and noisy soundscapes (Webster, Popper, and Fay 1992) and any organism subjected to selection pressures, is more likely to survive and reproduce if the conclusions it draws about the world from its sensory input are accurate (Hawking, 1989).

Thus, it is not unreasonable to hypothesize that if the brain activity can be suitably converted into sound with an appropriate sonification technique; the



human auditory system may offer some advantages in the detection and perception of the rapid and temporally complex patterns in the electrical activity of the human brain when presented as sound.

As will be outlined in [section 2.3](#), an auditory display has several potential advantages over a visual display for the presentation of the real-time EEG data.

For example, when the eyes are unavailable, whether this is due to blindness, the **eyes** being **closed** or the eyes being **busy** on another task, sonification can provide continuous detailed feedback without calling on the eyes. Furthermore Section 2.3 will present evidence that the auditory system receives sensory information to the brain more rapidly than the visual system and has a better temporal resolution. Section 2.3 will also propose nine potential strengths of the human auditory system and the way the brain processes sound that may be potentially useful for the real-time presentation of EEG with sonification for neurofeedback. It is these potential strengths that provide the motivation for using sonification to convey the real-time EEG for neurofeedback in this research.

## 1.2. [Motivation: Definition of the problem](#)

The primary motivation of this research was to develop and validate sonification techniques that are specifically appropriate to present the high temporal resolution and complex temporal dynamics of the EEG signal in real-time for the use of neurofeedback in order to facilitate learning.

However, as will be shown in the literature review in chapter three, the research field of EEG sonification has not yet achieved a sufficient critical mass on which to establish a firm methodological foundation. For example (as will be shown in Chapter 3), the majority of studies are pilot or proof of concept studies and very few have performed any quantitative analysis of the sonification output or a comparison between sonifications. Furthermore there is a striking lack of tools or methods to quantify a sonification's ability to convey the real-time EEG data or assess a participant's response to the sonification.

Therefore at present there is insufficient evidence in the research literature to establish which sonification technique would be more appropriate for neurofeedback or which features of a sonification would be more or less appropriate to represent specific features of the EEG signal.

On the other hand, a typical randomised double blind placebo controlled neurofeedback study will generally require a minimum of 30 participants to do at least 10 training sessions in order to show evidence of learning, which can be a time consuming and expensive experiment (Marzbani et al., 2016).

Given that there are numerous properties of the EEG signal that could be useful for neurofeedback and a myriad of ways they could be sonified, the idea of having to test each new iteration of a sonification with a full controlled neurofeedback study would be prohibitive and extremely inefficient.

Therefore it would be inappropriate to attempt to develop any new sonification techniques without being able to provide a reliable and quantitative assessment procedure that could establish the relative merits of a sonification technique or how well it can convey the EEG data. Furthermore it was

considered time consuming, inefficient and unethical to conduct an experiment with multiple sessions of neurofeedback with unfounded sonification techniques.

Consequently it was deemed necessary to develop a quantitative assessment protocol that could capture the ability of a sonification to convey the real-time EEG and assess how well people were able to perceive the EEG activity presented in the sound, then to test how well this protocol could predict a sonification technique's performance in a single session of neurofeedback.

### **1.3. Research Design**

This next section will present some of the factors and choices in the design of the experimental protocol used in this research.

#### **1.3.1. Tracking Task**

As will be discussed in section 3.6 on the 'Assessment of EEG Sonification' there are a number of quantitative methods that have been used to assess EEG Sonifications. However the EEG signal has very rapid fluctuations in amplitude and complex temporal dynamics and it was felt none of the current assessment methods can capture how well the full temporal dynamics of a real-time EEG sonification is perceived by the listener. Furthermore many of the current assessment methods, such as the 'Two-alternative Forced-Choice Method' (2AFC) where people listen to several 10 second sound files of sonified EEG and are then asked to decide which category the current file belongs to, is very

different to a typical neurofeedback session where people train for trials of three to five minutes for 5 to 10 trials per session for 10 to 20 sessions. Clearly, there is quite a difference between listening to a 10 second sound file and being asked to pick which group it belongs to, compared to listening to one's own real-time EEG for 20 minutes.

Thus for experiment 1 a continuous, non-verbal, real-time tracking task was designed, where people were asked to listen to the sound of an EEG sonification and try and track the activity they could hear in the sound with a mouse and a graphic slider on a computer screen.

Each of the three elements of this assessment task are critical. As was mentioned above and will be explained in more detail in section 2.2 on neurofeedback, the primary challenge in neurofeedback is to try and identify the brain activity in a rapid, continuous, complex and noisy signal.

Consequently the assessment of a sonification's ability to convey this data must reflect the nature of the listening task, which is continuous, non-verbal and real-time. Thus the concept of the tracking task was to allow the participants to listen to a sonification in a manner that is similar to a typical neurofeedback session, whilst simultaneously and continuously reporting on their perception of the sonification, without interfering with the task of listening to the sonification.

The issue of exactly what is meant by the term "tracking the activity" could be somewhat contentious and the results of the third experiment demonstrated that the instructions in the tracking task had a greater impact on tracking accuracy scores than the type of sonification technique.

The intention was to create tracking instructions, which would be sufficiently ambiguous to allow each person to interpret what they could perceive in the sound for themselves and then try and track that activity.

This tracking task was not intended as an assessment on listening acuity and the question was not whether people can track the volume or frequency per se. Rather the aim was to determine whether the listener is able to perceive EEG activity from the sonification. Put another way, when a person listens to a real-time sonification of real EEG data, is what they hear in the sound, capable of conveying information about the EEG activity.

Of course as with all things to do with human perception, this is a very subjective question and in the first and third experiment there was a considerable variation in how people responded to the task. As a consequence the tracking task is envisaged as a comparative measure, where two or more sonifications are assessed by the same individuals, so the relative merits can be determined, as a preliminary assessment prior to a typical neurofeedback type study.

Thus the tracking task was designed to test the full processing chain, of the transformation of the brain activity (i.e. the EEG data) into sonification (i.e. the sound), and then into the participant's perception and then into a motor action of moving the mouse (i.e. the tracking). By correlating the original EEG data that generated the sonification with the tracking data a quantitative tracking score can be computed.

Evidently having to make a motor response to such a rapid signal would introduce delays between the tracking and EEG data; however this should

affect all sonification techniques equally and the delay can be taken into account.

Accordingly the tracking task could provide a quantitative assessment of how well people can perceive a sonification and infer the technique's ability to convey the temporal dynamics of real-time EEG. This could help the establishment of a baseline measure that subsequent sonification techniques can be compared against. Furthermore it can provide a comparative measure between two or more sonifications.

If the tracking task could predict how well a sonification technique would be at conveying EEG data for neurofeedback training, then it could be a useful tool for the rapid prototyping and development of sonification techniques.

This could help in the design of more efficient sonification techniques that could reduce the duration and number of neurofeedback sessions required to make lasting changes in the brain, which could help many people to improve their health and Performance.

### 1.3.2. Choice of Sonification Techniques

In order to reduce the number of subjective design decisions required in the sonification mapping to establish a baseline, two conceptually and technically simple real-time capable sonification techniques were chosen and used in all three experiments.

As will be explained in [section 4.2.3](#) the **Amplitude Modulation** (AM) sonification technique uses variations in the power of the EEG to modify the **volume** of a pure tone, i.e. as the power of the EEG goes up so too does the volume of a

tone. The **Frequency Modulation** (FM) uses changes in the power of the EEG to modify the **frequency** of a pure tone, so as the power of the EEG goes up the frequency goes up. The AM and FM sonification techniques could be considered the most basic of sonification techniques capable of the real-time presentation of EEG data and therefore an appropriate place to start in order to establish a baseline that more complex sonifications can be compared against.

### 1.3.3. One and Two-Channel Sonifications

One of the motivations for using sonification for neurofeedback is the potential it offers to present multiple simultaneous streams of real-time EEG data in a manner that can facilitate the perception of the complex brain activity.

Consequently, as well as comparing the two different sonification techniques, in order to test how well people are able to perceive more than one simultaneous stream of sonified EEG data. This research used both a single channel sonification which took the EEG data from one electrode and turned it into one channel of sound and two-channel sonification which used the data from two EEG electrodes and created two separate streams of sound, one in each ear.

### 1.3.4. Choice of Electroencephalography Parameter

There are many parameters that can be derived from the electroencephalogram and the Alpha band is probably the most well-known.

The Alpha band was chosen to be used in all three experiments, because it is a high amplitude signal that is easily identified in the raw EEG trace and is the dominant frequency in most people when their eyes are closed (Kropotov,

2010), making it easy to measure. Also, probably because it was the first brain wave to be identified in humans (Berger, 1929), its cognitive concomitances are relatively well-known (Kropotov, 2010). It is associated with a reduction in glucose and oxygen consumption (Cook et al., 1998), which is the fuel of the brain (see [section 2.1.6](#)). Alpha is known as the brain's idling rhythm and an increase in the Alpha level is associated with an elevation in relaxation as well as a decrease in activation of the brain regions producing the Alpha activity (Kropotov, 2010).

As identified in [section 2.1.9](#), Alpha has interesting temporal dynamics in the decasecond time range that could be particularly suitable for the sonic presentation of its activity for neurofeedback.

Alpha was the first brain wave to be trained with neurofeedback back in the 1960s (Kamiya, 1962) and has been used in many studies since. It is probably one of the easiest brain wave to train as many people can feel its presence or absence. Also because it is associated with relaxation it is probably the safest brainwave to train and it would also be useful to train the Alpha with the eyes closed to facilitate relaxation.

Furthermore, the Alpha EEG band could be used in the two-channel sonification training, with a measure called 'Frontal Alpha Asymmetry' (FAA), which measures two channels of Alpha brain wave from the left and right frontal cortex (Davidson, 2004a).

As will be discussed in [section 2.1.10](#) the FAA can be seen as a measure of approach or withdrawal behaviour and as a proxy for mood. Again there have



been decades of research into this measure and many neurofeedback studies have trained the FAA.

### **1.3.5. Single Session of Neurofeedback Training**

Although it is usual to train for multiple sessions in most neurofeedback studies (Marzbani et al., 2016), the literature review has identified several little known experiments that have successfully trained changes in both physiological and psychometric measures with a single session of EEG sonification neurofeedback. (See [Table 3.7.13](#))

As discussed at the beginning of this section, it was felt to be premature and a waste of participant's time to conduct a multiple session neurofeedback experiment with an unproven sonification technique.

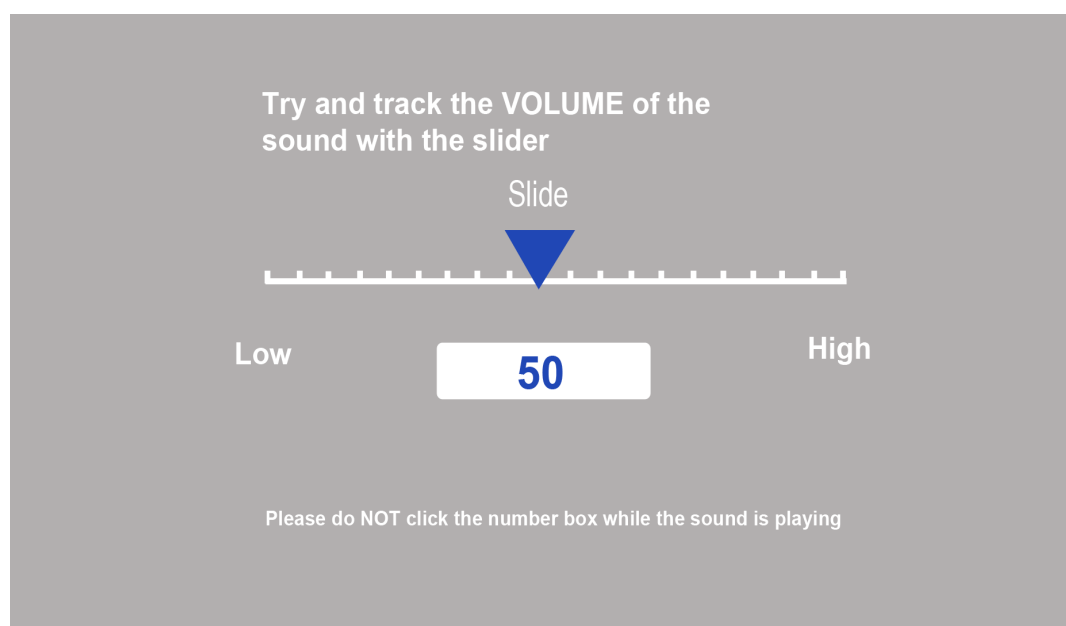
Therefore the second experiment conducted a single session per participant, consisting of both the AM and FM Alpha sonification neurofeedback training tasks, in order to assess how well the tracking task could predict the training outcomes. However, because of the possible confounding problems of training two different sonification techniques in the same session the third experiment consisted of two sessions, one for each sonification technique.

### **1.3.6. Experimental Design**

Thus a series of three experiments were designed that sequentially built upon each other in order to try and establish a baseline of how well a sonification technique could convey real-time EEG data in a manner appropriate for neurofeedback.

The first experiment used a single channel of AM and FM sonification of pre-recorded EEG and asked people to try to track the activity they could hear in the sound with a mouse and a graphic slider on a computer screen. Figure 1.3.6, shows an example of the tracking screen for the AM sonification, where participants are instructed to move the slider with the mouse to the right as the volume of the sonification increases and to the left as the volume decreases. For the FM sonification the instructions were the same but used the word frequency instead of volume.

The tracking task was designed to assess how accurately people could perceive the real-time EEG data when converted into sound and test the full processing chain, of the conversion of the EEG data into sound, then the participant's ability to perceive the data in the sound and finally their ability to move the slider accordingly. (See section 4.2.4.)



**Figure 1.3.6:** Example of the Tracking Screen for the AM sonification.

The second experiment used the same two single channel sonification techniques and asked people to try to modify their own physiological activity by listening to a real-time sonification of their own EEG data in a single session. Participants were asked to try and lower the amplitude for AM or frequency for FM of the sonification. This would decrease the alpha levels in the left prefrontal cortex and increase activation, which in theory should increase approach behaviour and positive affect (see section 2.1.10 for details). However, participants were not made aware of this intended effect.

The third experiment combined the tracking task from the first experiment and training task from the second experiment with the same AM and FM sonification techniques but this time with a two-channel sonification and two test sessions, one for each sonification technique. In the training task participants were instructed to either increase the amplitude on the right and or decrease the amplitude on the left for the AM sonification, with a similar effect as in experiment 2.

The combination of all three experiments allows a 'within subject' comparison between two different sonification techniques for both one and two-channel EEG sonification, as well as a 'between subjects' comparison of the one and two-channel sonifications.

## **1.4. Conclusion**

This chapter has identified the overlapping area created by the three domains of Electroencephalography, Neurofeedback and Sonification where this research resides. It presented the motivations of this research and outline the structure of this dissertation.

The next chapter will give a more in-depth explanation of these three domains and present some of the theoretical, technological and methodological issues that will be critical for this research.

Chapter 3 will review the EEG sonification research literature. Chapter 4 will present the first experiment which involves a 'Listening and Tracking' task. Chapter 5 will discuss experiment 2, a single channel Real-Time EEG Sonification Neurofeedback experiment. Chapter 6 explains experiment 3, which combines a tracking and Neurofeedback training experiment with 2 Channel Real-Time EEG Sonifications. Finally Chapter 7 provides a summary and conclusion of the dissertation.

## Chapter 2: EEG, Neurofeedback & Sonification

Given that the overall research question is to find out how real-time electroencephalogram (EEG) data can be sonified to support neurofeedback,

This chapter will give a brief overview of some of the key knowledge domains that will be referred to in the following chapters.

The first [section 2.1](#) will present EEG and relevant historical, technical and physiological aspects. [Section 2.2](#) will focus on neurofeedback, its application areas, subdomains and some salient technical aspects and learning theories. The last [section 2.3](#) will highlight some of the motivations for using sonification to convey real-time EEG for neurofeedback.

A review of the research literature is presented in the next chapter.

### 2.1. Introduction to Electroencephalography

**Electroencephalography** (EEG) is a **safe** and **non-invasive** measure of the weak electrical activity of the human brain as measured from the scalp. It involves measuring a noisy, low amplitude signal (up to 100 microvolts), with a typical amplitude resolution of 1 microvolt, and a temporal resolution of around 2 milliseconds. EEG has complex temporal dynamics in the millisecond to decasecond time scale, with a frequency range of 0 to over 70 Hz. The raw EEG has a distinct morphology (pattern of the wave form) and can be sub-divided into different frequency bands representing specific cognitive processes (Kropotov, 2010). The EEG signal can be difficult to interpret, and neurologists

and epileptologists specialise for several years in order to be able to make clinical diagnoses from the EEG signal (The General Medical Council, 2017).

### 2.1.1. A Brief History of EEG

The first recorded example of an EEG measurement was by the English physician Richard **Caton** (1842–1926) in 1875 in a paper called, “**The electric currents of the brain**”, and presented at the British Medical Association in Edinburgh. He recorded from the brain's surfaces of a living rabbit and monkey using a galvanometer (From Luigi Galvani 1770s) and remarkably presciently he stated that “The electric currents of the grey matter appear to have a relation to its function” (Caton, 1875).

The German Professor of Neurology, Hans **Berger** (1873–1941) worked in secret for many years before publishing his work on the non-invasive recording of EEG from humans in 1929 and is generally considered the father of human EEG (Berger, 1929).

By 1934, certain spikey looking patterns that could be seen in the trace of the EEG had been identified as a marker of epilepsy, and in World War II the United States Army Air Corps was using the EEG to screen pilots for epilepsy (Keiper, 2006).

EEG is currently used to diagnose epilepsy (NICE, 2018), sleep disorders, coma and brain death (Dou et al., 2014).

### 2.1.2. Electroencephalography and quantitative EEG

With the development of digital EEG hardware it became possible to use sophisticated digital signal processing techniques to analyse EEG, using analytical techniques such as Fourier analysis, wavelet analysis and event related desynchronisation. These approaches are referred to collectively as quantitative electroencephalography (qEEG) (Hammond et al., 2004). The amassing of databases of quantitative EEG normative data both for healthy and patient groups led to new clinical applications (Budzynski et al., 2009), and in 1997 the American Academy of Neurology and the American Clinical Neurophysiology Society concluded that qEEG in conjunction with traditional EEG interpretation, should be considered “investigational for clinical use in post-concussion syndrome, mild-to-moderate head injury, learning disability, attention disorders, schizophrenia, depression, alcoholism, and drug abuse” (Nuwer, 1997). More recently, qEEG has been used to help diagnose a range of conditions, such as Attention Deficit Hyperactivity Disorder (ADHD), Schizophrenia, Addiction, Obsessive-Compulsive Disorder, Depression and Alzheimer's (Kropotov, 2010) as well as stress related conditions.

Having a qEEG assessment to identify the areas of the brain that are either over or under activated to establish training protocols for neurofeedback and other therapeutic interventions is becoming standard practice (Walker, 2004) and with these new advances, EEG is experiencing somewhat of a renaissance both in research and clinically (Kropotov, 2010).

In order to capture the brain in different levels of arousal and acquire sufficient data for a stable<sup>2</sup> measurement, a typical qEEG assessment battery for diagnostic purposes consists of recording the EEG from at least 19 locations over the head in several trials. Usually this will consist of recording a person for five minutes with their eyes closed and five minutes with their eyes open and then a 20 minute attention task (Hammond et al., 2004). Typically the processing of the EEG data is done **off-line**, as it can take several hours to analyse and identify any clinical markers (Gabard-Durnam et al., 2018).

The use of real-time EEG has three main application areas: **Brain-Computer Interface** (BCI), continuous **EEG Monitoring** in Operating Room and in Intensive Care Units and real-time EEG presentation for **neurofeedback** (Väljamäe et al., 2013). (**Neurofeedback** will be discussed later in [section 2.2](#)). With the growing body of knowledge about the electrophysiology of the human brain and the arrival of cheap and consumer grade EEG systems these fields are also experiencing increasing interest.

### 2.1.3. Temporal vs. Spatial Resolution

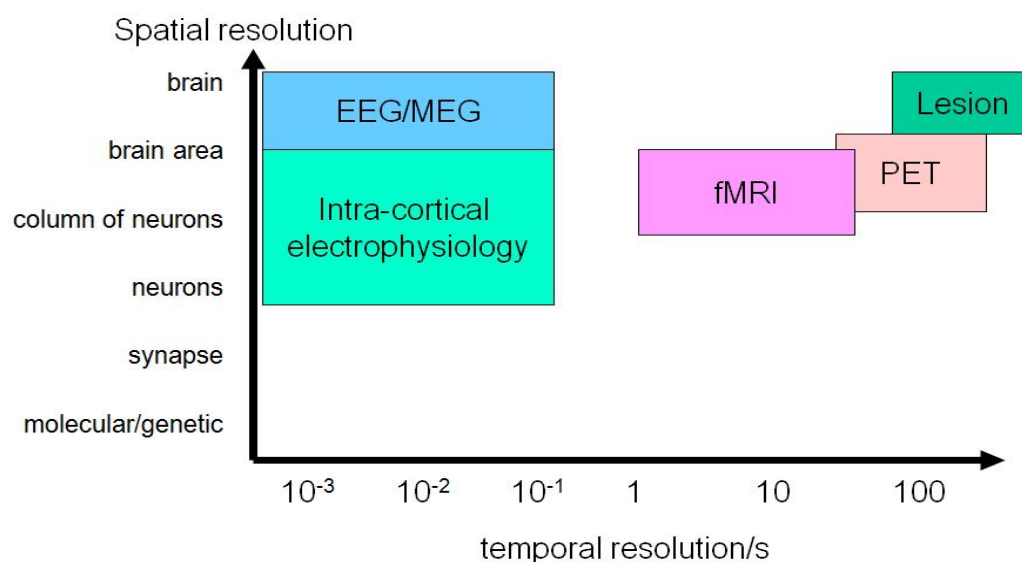
The main advantage EEG has over other neuroimaging techniques (besides the hardware being hundreds of times cheaper), is its high temporal resolution. However, there is a trade-off, in that spatial resolution is low compared with other brain imaging methods.

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<sup>2</sup> A stable measurement is a repeatable measure over short and long time intervals with a high test-retest reliability. EEG frequency components in resting and task conditions have a test-retest reliability of between R 0.7 & R 0.9. (McEvoy et al., 2000)



## When and Where: Temporal-Vs-Spatial resolution



**Figure 2.1.3:** Shows the temporal vs. spatial resolution of the main neuroimaging techniques. The horizontal 'X' axis is the temporal granularity, measured in seconds. The vertical 'Y' axis shows the spatial resolution, ranging from microscopic scale at molecular level, up to the centimetre scale of the whole brain. (Adapted from Churchland & Sejnowski, (1988)).

**Figure 2.1.3** shows that **EEG**, Magnetoencephalogram (**MEG**) and **intracranial** electrical recordings all have temporal resolutions several orders of magnitude higher than the other techniques on the temporal scale. But Functional Magnetic Resonance Imaging (**fMRI**) and Positron Emission Tomography (**PET**) have a spatial resolution in the order of millimetres, whereas EEG and MEG have a spatial resolution of several centimetres.

#### 2.1.4. qEEG: Frequency, Amplitude and Location

Quantitative EEG (qEEG) has three primary measures, Frequency, Amplitude and Location. EEG has a frequency range of 0 to over 70 Hz which is called the **Raw** EEG and is divided into several sub-frequency bands, which are roughly associated with arousal states (see [Table 2.1.4.1](#)). So, low frequencies are associated with low arousal and higher frequency with high arousal. The frequency bands can vary from study to study, but are generally given as:

EEG Band Names	Frequency	Brain Function
<b>Raw EEG</b>	0 to over 70 Hz	
<b>Delta</b>	2 to 4 Hz	seen in deep sleep
<b>Theta</b>	4 to 8 Hz	linked to drowsiness and memory
<b>Alpha</b>	8 to 12 Hz	relaxed or inhibition state
<b>Beta 1</b>	13 to 21	attention and arousal
<b>Beta 2</b>	21 to 30 Hz	a sign of over arousal
<b>Gamma</b>	over 30 Hz	to do with memory binding

***Table 2.1.4.1:** Shows the typical frequency ranges and general brain function associated with the different EEG bands. ([Cacioppo et al., 2007, p59])*

The **amplitude** is measured in microvolts and a salient feature of the EEG is the relative amount of the different frequency bands in relation to each other. For example, a high level of Beta on its own may not be an indicator of attention, but the level of beta relative to theta (in the front of the brain) is related to drowsiness (Kropotov, 2010).

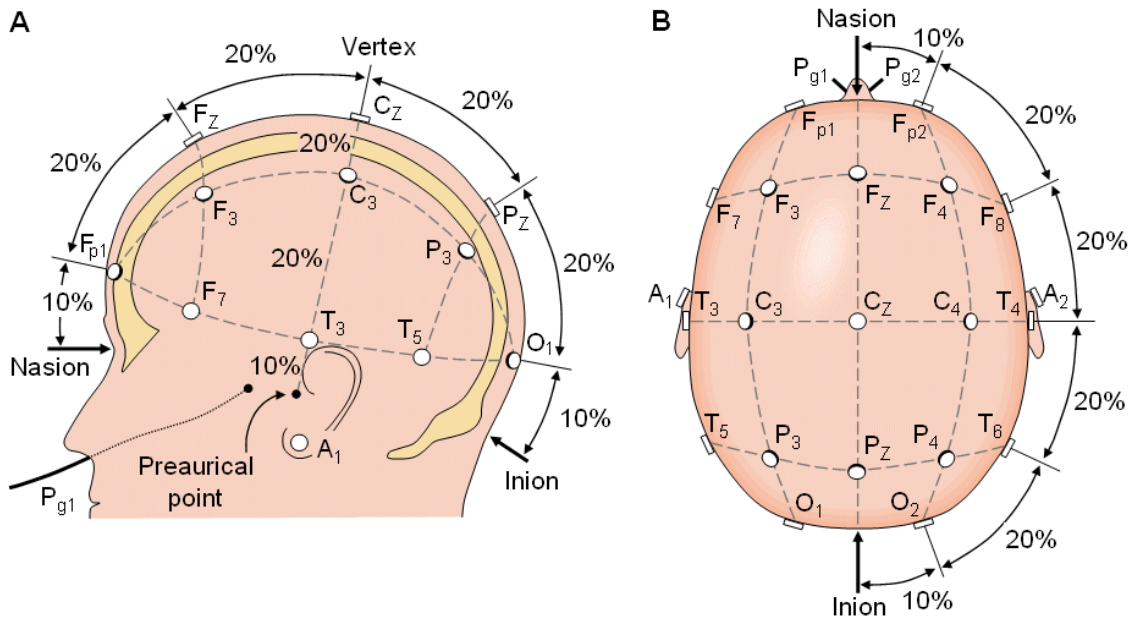
### 2.1.5. Electrode Placement

The brain creates temporary functional networks that connect for a short time to perform specific tasks also called effective connectivity (Friston et al., 1993). A particular function like 'recognising a face' may be associated with a particular location in the brain that specialises in that function (Ward, 2010) but more importantly there will also be a specialised network of other areas that work together to support that function. Consequently, the sites at which EEG voltages are measured will reflect activities associated with the brain regions directly under the electrodes, but they will also reflect a mix of activities from functionally related brain regions, as well as more general activity from other brain regions. More generally, voltages measured are affected by a process called volume conductance. (Kropotov, 2010)

Spatial resolution is a measure of how accurately an activity can be located in space. If electrodes are surgically placed inside the cortex (intracranial iEEG), they have a spatial resolution of 0.5 to 3 mm and can record the activity of a single neuron. In Electrocorticography (ECoG) the electrodes are placed on the surface of the cortex under the skull, this gives a spatial resolution of 1 cm - or better for higher frequencies (Muller et al., 2016).

Unfortunately, as the skull acts as a spatial filter it "blurs" the weak EEG signals, so the spatial resolution of electrodes from the scalp is generally given as around 3 cm (Kropotov, 2010). Despite this, when multiple electrodes are used on the scalp 'spatial deblurring' algorithms can improve the spatial resolution

(Burle et al., 2015). With 19 scalp electrodes the LORETA algorithm (Pascual-marqui et al., 2002) can localise activity to 7 millimetre voxels<sup>3</sup>.



**Figure 2.1.5.1:** The international 10-20 electrode placement system, A: sagittal plane. B: Transverse or Horizontal plane.

In [figure 2.1.5.1](#) the nomenclature, dating from 1958 (Jasper, 1958), for the locations referred to on the scalp is called the 'international 10-20' electrode placement system and is the most widely used electrode layout definition. The odd numbers are on the left hand side of the head and even numbers are on the right. Lower numbers are closer to the centre line and increase as they move out towards the ears. "O" stands for Occipital lobe, "T" is Temporal lobe, "P" is for Parietal lobe, "C" Centre or Sensory motor strip, "F" is Frontal and "Fp" is

<sup>3</sup> a three-dimensional region or 3D pixel

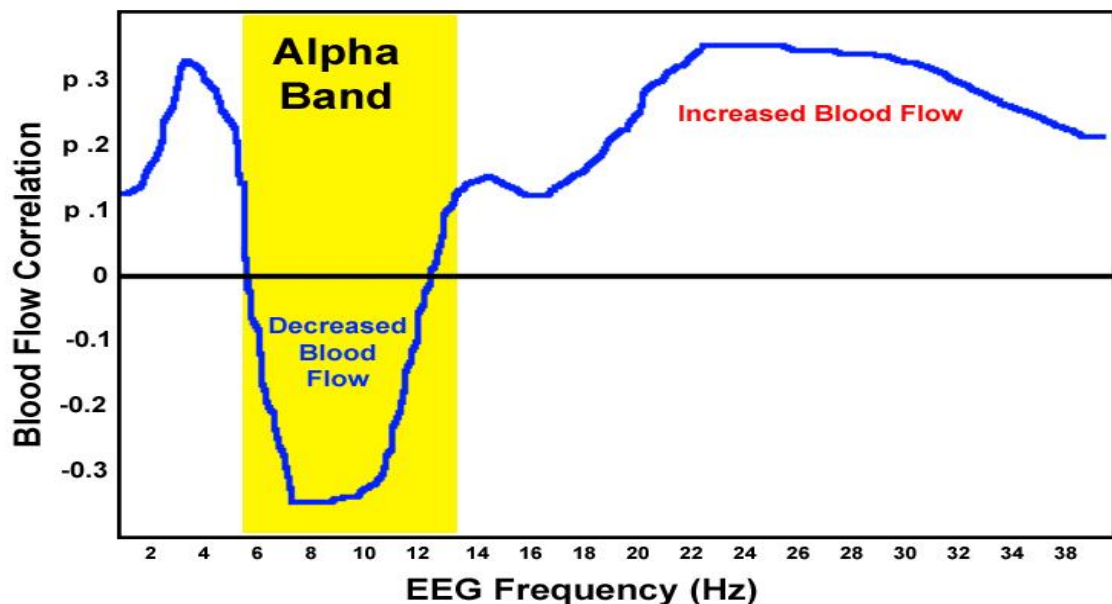
for Frontal Pole, i.e. the very front over the eyes. A1 and A2 are the left and right earlobes and M1 and M2 are the mastoids, the bone just behind the ears.

So for example **F3** is over the left frontal cortex and **Cz** is in the centre of the scalp.

The name 10-20 derives from the fact that the distance between the bridge of the nose (Nasion) and the back of the head (Inion) from front to back (sagittal plane) and from ear to ear on the coronal plane, is sub-divided, into distances of either 10% or 20% of the total span, as shown in [figure 2.1.5.1](#) to give electrode locations.

#### 2.1.6. EEG and Brain Blood Oxygen

The **Alpha** brainwave was the first to be discovered in the human brain by Hans Berger (1929) and even in his early work he identified the relationship with brain activity. Berger reported that the alpha would increase in amplitude in the back of the brain when the eyes were closed and disappear when the eyes were opened, this is called alpha blocking. [Figure 2.1.6.1](#) shows how the oxygen levels in the blood as measured by positron emission tomography (PET) correlate with the EEG frequency.

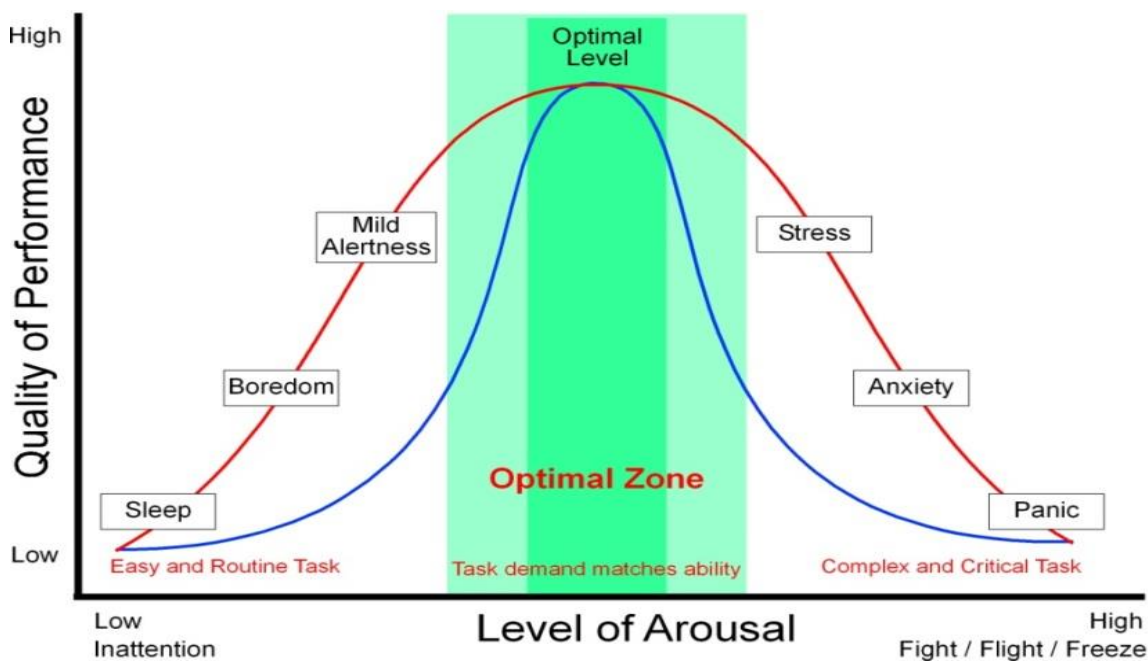


**Figure 2.1.6.1:** Shows blood brain oxygen levels as measured by positron emission tomography in relation to the EEG frequency. Adapted by the author from, (Cook et al., 1998). The horizontal axis is the frequency of the EEG and the vertical axis shows the PET oxygen levels in the blood. Positive numbers going up from zero show an increase in oxygen levels and the negative numbers show a reduction in oxygen levels and therefore brain activity.

Glucose and Oxygen are the fuel for the brain (Mergenthaler et al., 2013), and the brain consumes around 20% of the oxygen that the body uses (Ward, 2010, p. 51), **figure 2.1.6.1** shows how alpha power is inversely correlated with blood oxygen levels. This makes alpha power a useful index of brain activity, or by inference arousal (Fan et al., 2012), because as the amount of alpha brainwave increases, the amount of brain activity decreases.

### 2.1.7. Arousal

The widely cited Yerkes Dodson curve (Yerkes and Dodson, 1908) in [figure 2.1.7.1](#), shows the relationship between arousal and performance; as a person's arousal increases ('X' axis) their performance ('Y' axis) tends to increase until it reaches an optimal level, then the performance starts to decline as arousal carries on increasing. The red line gives an example of someone who performs better over a wide range of arousal from boredom to anxiety. By contrast, the blue line shows someone who performs well only within a more narrow range of arousal, although both people can achieve the same level of optimal performance (in the dark green zone).



**Figure 2.1.7.1:** Schematic of the Yerkes Dodson curve of the relationship between arousal and performance for a difficult task (modified by author). The red line indicates a person who performs well over a wider range of arousal, by contrast with the blue line, representing someone who performs well only in a narrower range of arousal.

Therefore, when considering the arousal level demanded by a task, this may need to be balanced by consideration of a person's individual response to arousal level. So for example, in a boring task a person might need to find ways of raising their arousal to avoid making inattentive errors of omission. By contrast, in a stressful task people might benefit from reducing their arousal in order to prevent errors of commission by responding too quickly or inappropriately (Riccio et al., 2002).

EEG can reflect the spontaneous cortical self-regulation of the brain and can give information about which areas of the brain are over or under aroused, and whether the brain is functioning optimally. It is possible to have different parts of the brain in all three arousal states of over, under and optimal arousal, at the same time, which in some circumstances could be a clinical marker (Kropotov, 2016).

As regards the effects of individual differences, Grey Walter (Walter et al., 1964), showed that when a person is getting ready to make a motor response such as pushing a button in reaction to a light signal, a slow negative potential is generated in the cortex called the 'contingent negative variation' (CNV) or the 'readiness potential'. Walter showed the level of this potential is affected by the arousal of the individual, as reflected by the Yerkes Dodson curve. That is to say, the contingent negative variation is lower when an individual's arousal is too high or too low, and highest with an intermediate level of arousal.

Hans Eysenck (1967) showed that Extroverts and Introverts differ in their cortical arousal. Introverts have greater baseline cortical activity and thus find



stimulating situations, like social encounters excessively arousing so they tend to seek solitary situations in order to return their own arousal level to a more acceptable middle range. Conversely extroverts have a lower level of arousal and seek stimulating situations in order to increase their own arousal. These discoveries were the beginning of the research field of individual differences in personality theory.

A pathological case would be a person with an attention disorder who may have an under-aroused frontal cortex, which is where the executive function is located, but an over aroused sensory motor strip. This would lead to impulsive behaviour with lots of errors of commission (responding when one shouldn't) and the reduced ability to self-monitor the errors (Kropotov et al., 2013).

Thus, information as to the arousal level of different brain regions can be used to decide if or in which direction, the arousal of different brain areas should be trained.

#### **2.1.8. EEG parameter Selection**

Prior to the formal literature survey, which follows in the next chapter, and the experiments, presented in subsequent chapters, a number of informal interviews were conducted with eminent researchers in the field of both EEG and sonification, both to focus the research question and to help avoid any hidden technical pitfalls. One particular concern was to establish criteria for the selection of appropriate EEG parameters as the focus of sonification experiments in the dissertation.

In a formative interview at the beginning of this research project the neurologist Dr Gerold Baier (also one of the most prolific authors on EEG sonification) gave

the advice, "stick to a well-known EEG parameter, something that mainstream neurology will accept! Or it does not matter how good the work is, they will just look at the EEG parameter and dismiss the rest". (Baier, 2012, personal communication) This is perhaps why most of his work on EEG sonification has focused on epilepsy, as epilepsy generates very distinctive spiky looking activity in the EEG and EEG is considered the "gold standard" for identifying and diagnosing epilepsy (Tatum et al., 2007).

Although this is an excellent candidate criterion, for parameter choice one problem with applying it is that mainstream neurology only considers the raw EEG to be an appropriate clinical parameter for conditions such as epilepsy, head injury and sleep disorders. However, working with these populations would raise considerable ethical issues with a novel intervention and would generally be beyond the scope of doctoral research.

A second problem with acting on this candidate criterion is that quantitative EEG has established many EEG parameters as having diagnostic utility, but as with many disciplines, practitioners can be slow to adopt new practices or accept new evidence. Therefore what is considered an established EEG parameter can be contested (Kropotov, 2010).

Moving onto a second candidate criterion for parameter choice, the EEG parameter should have a known mental concomitance, so that any manipulation of the EEG parameter can be independently validated with psychometric measures. After all, there is no point showing that an EEG parameter can be modified if it has no effect on any behaviours or mental states.

The third candidate criterion is that any prospective EEG parameter is going to be used in a neurofeedback training study; it must be something that people can perceive and train. This is a relatively easy criterion to identify and fulfil, as there are decades of neurofeedback studies with a large number of EEG parameters to choose from.

Another concern is to capitalise on the strengths of sonification identified in the previous section, by choosing an EEG parameter with high temporal dynamics.

Yet another concern is to pick an EEG parameter that is safe to train. It is generally stated in the literature that there are no known adverse side effects from neurofeedback training. However, it is certainly possible to over or under arouse people, even healthy control participants (Hammond and Kirk, 2008) particularly if a diagnostic qEEG assessment has not been carried out prior to training.

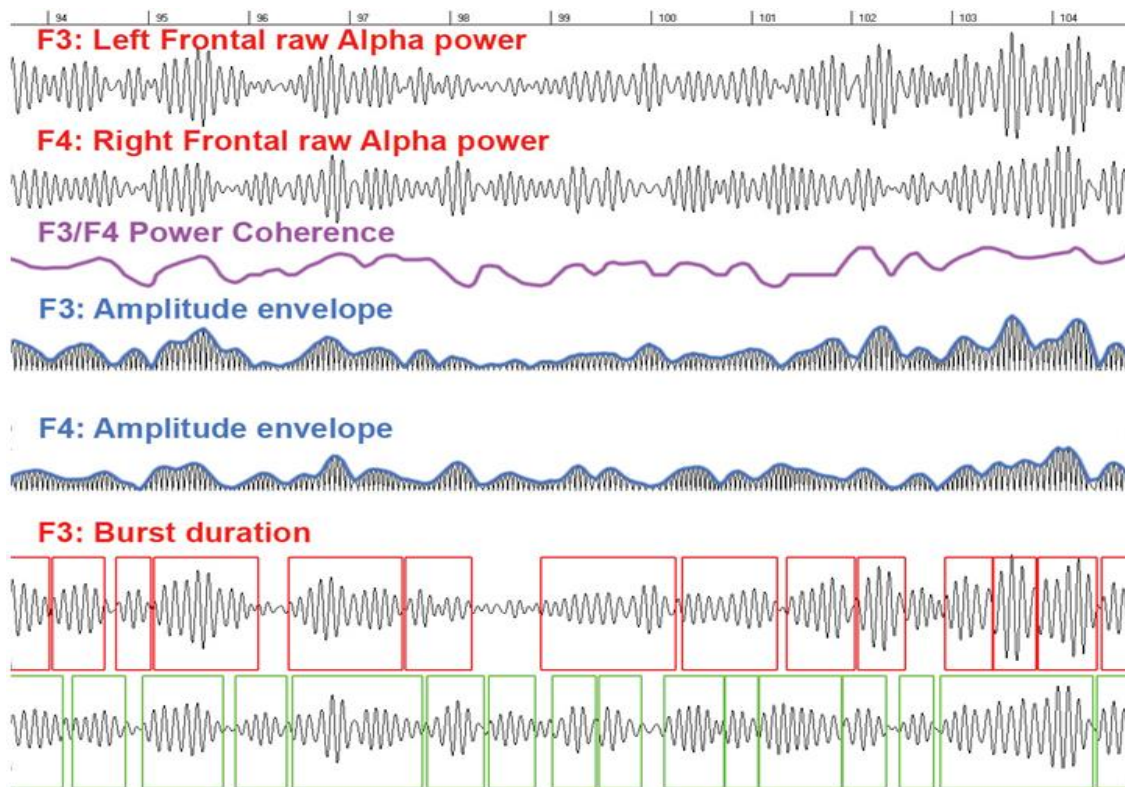
Therefore, assembling the above considerations, the EEG parameter should:

- **be an established EEG parameter**
- **have known mental concomitance**
- **have a high temporal dynamics**
- **be perceivable by a trainee**
- **be modifiable by a trainee**
- **be safe to train**

### 2.1.9. Alpha Brainwave

In an interview with Dr Paul Swingle who has a very successful neurofeedback practise in Vancouver and was a Lecturer in Psychiatry at Harvard Medical School and a Professor of Psychology at University of Ottawa, he advised that this research should focus on the Alpha brainwaves, not only because it is a well-known EEG parameter but because it is “where everything happens” (Swingle, 2014, personal communication).

The alpha brain waves have several advantages for this research; firstly it is a high amplitude signal that is easy to see in the raw EEG trace (Kropotov, 2010). Being the first human EEG frequency band to be discovered (Berger, 1929), it has a long history and many studies, therefore there is a lot known about its cognitive concomitance (Kropotov, 2010). Also, as will be presented in [chapter 3](#), there have been many neurofeedback studies using the alpha band and as they are often associated with relaxation, being able to do the neurofeedback training with the eyes closed would be desirable. Furthermore as the only likely risk in a healthy population with neurofeedback training is the possibility of over arousing the person, therefore as the training of alpha brainwaves is associated with relaxation, this is unlikely to be a concern. What is more, the alpha amplitude envelope (i.e. the waxing and waning of the amplitude, see [Figure 2.1.9.1](#)) has some interesting temporal dynamics with oscillatory patterns over several seconds that could be in an interesting time range for sonification.



**Figure 2.1.9.1:** Shows a schematic of 10 seconds of EEG Alpha activity; the top two traces show the typical Alpha EEG fluctuations that occur on the left and right frontal cortex. The purple trace shows the coherence between the two top Alpha traces. The middle two blue traces show the rectified amplitude envelope of the top two Alpha traces. The bottom two traces are the same as the top two but the red and green boxes highlight the “Alpha Burst” and duration, as well as the quiescent periods between the bursts.

### 2.1.10. Frontal Alpha Asymmetry

Interestingly, Alpha brainwaves can give more than just information about a person's state of arousal. Professor **Richard Davidson** is a researcher of Affective<sup>4</sup> Neuroscience and has carried out decades of research ranging from rat studies in the Lab to longitudinal studies with adults in the real world, on the neuronal mechanisms underlying the individual differences in affect and emotion. He suggests that affect is processed in the frontal cortex and that greater activation of the left frontal cortex of the brain, in comparison to the right, is associated with more positive emotions. By contrast, greater activation of the right frontal cortex is associated with more negative emotions (Davidson et al., 1999).

Davidson points out that one of the most salient characteristics of emotion is the individual differences in response people have to a negative event, such as the threshold of response, magnitude of response, latency to peak of response and recovery function (Davidson, 2004b).

An emotional state has a physiological basis that can create an involuntary urge to act, as well as a conscious feeling that can generate behavioural patterns. Emotions have a functional evolutionary basis to help initiate activation when survival is at stake. For example fear protects by initiating withdrawal, whereas anger intimidates others and energises an individual for attack or defence (Al-Shawaf et al., 2015).

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<sup>4</sup> In Psychology the word affect refers to a feeling or emotion, see [section 2.1.11](#).

Building on Davidson's work Harmon-Jones et al. (Harmon-Jones et al., 2010; Harmon-Jones and Allen, 1998) suggest that greater activation of the left prefrontal cortex (PFC) of the brain (more specifically the orbital PFC and as a consequence the dorsolateral PFC (Davidson, 2004a)), is associated not only with positive emotion but also with elevated approach motivation i.e. seeking stimulation. Whereas greater activation of the right PFC shows not only negative emotion but also elevated withdrawal motivation (i.e. wanting to withdrawal from the world or lower the arousal).

As explained in [section 2.1.6.1](#) above, the alpha brainwave amplitude is inversely associated to brain activity; therefore a decrease in alpha activity in the left frontal cortex, in relationship to the right, would indicate an increase in activity and therefore an increase in positive or approach behaviour and conversely a decrease in alpha waves on the right would indicate an increase in negative emotions or withdrawal behaviour. This has come to be known as Frontal Alpha Asymmetry (FAA).

Whilst there is still some debate about exactly how to interpret these findings and with many of the technical issues on how frontal alpha asymmetry should be measured (Allen, Coan, et al., 2004). There is an impressive number and variety of studies over the last 30 years to provide sufficient evidence for the utility of this parameter.

For example, there are studies showing that infants have a greater left frontal activation in response to videos of people laughing (Davidson and Fox, 1982) and that neonates show a greater left activation when drinking sweet solution than with citric acid solution (Fox and Davidson, 1986) and that right frontal

activation predicts infants who cried in response to brief maternal separation (Davidson and Fox, 1989). Deslandes et al. (2008) showed that depressive elderly participants showed relatively greater right frontal activity whereas healthy elderly showed relatively greater left frontal activity.

Davidson has shown that people with more left-activation, exhibit higher levels of natural killer cells, a marker of better Immune function, than right activated people (Davidson et al., 1999) and that participants with higher levels of right-prefrontal EEG activation showed a poorer immune response to a vaccination for influenza (Rosenkranz et al., 2003).

Arns et al. showed that right dominant frontal alpha asymmetry is associated with treatment response and remission to medication in females with major depression (but not in males) (Arns et al., 2016).

In order to prevent relapse of depression among people with a history of suicidal depression, Barnhofer et al. (2007) compared an 8-week meditation/mindfulness-based cognitive therapy course to 'treatment-as-usual' under the care of their physician. Barnhofer found that only the people in the treatment-as-usual group had an increase in severity of depressive symptoms and a decrease in relative left-frontal Alpha activation, whereas the mindfulness group did not show an increase in symptoms or a decrease in left-frontal Alpha.

Therefore Frontal Alpha Asymmetry could be considered an established EEG parameter with known mental concomitance, which people can perceive and train.



Although the real-time temporal dynamics of a single alpha channel could be considered as 'known' as it has been used in a large number of neurofeedback studies (See section 3.7), the temporal dynamics of the asymmetry of two channels must be considered unknown at this stage as the majority of studies that use this FAA index tend to average the alpha asymmetry over at least 2 to 12 minutes (Allen and Cohen, 2010).

Regarding the safety of training the Frontal Alpha Asymmetry parameter, as it reflects both positive and negative affect, there is a potential to train a negative response by training the alpha down of the right side or up on the left, but of course this research will not seek to do this.

#### 2.1.11. Arousal and Valence

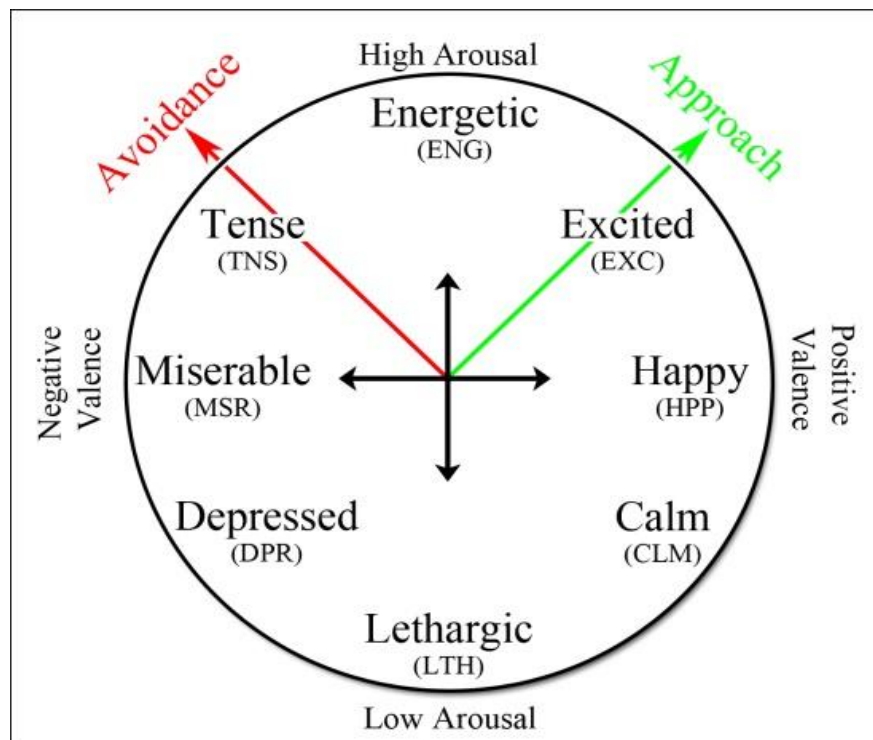
One way of conceptualising the interaction between arousal and the positive and negative emotions categorized by the Frontal Alpha Asymmetry was developed by **James Russell** and called the "**circumplex model of affect**" (Russell, 1980).

In the field of psychology the word 'affect' refers to a feeling, mood or emotion and is one of the three main domain divisions i.e. 'affect', 'behaviour', and 'cognition' sometimes called the ABC of psychology (Breckler, 1984).

The word 'valence' is used to denote the nature of the 'affect', i.e. whether it is positive or negative. So for example the 'affect' of joy would have a 'positive valence' and fear has a 'negative valence'.

Russell suggests that an emotional experience can be described by two orthogonal factors on a two dimensional plane. The vertical axis represents

arousal, which is a measure of how calming or exciting an experience is, while the horizontal axis represents valence, a measure of how negative or positive an emotion is.



**Figure 2.1.11:** Shows a 2-D schematic of the Arousal-Valence circumplex model of affect. The horizontal axis represents valence from negative on the left to positive on the right. The vertical axis represents arousal with low on the bottom to high on the top. (adapted from (Knutson et al., 2014). The avoidance and approach axes are superimposed in red and green. Around the outside are the 8 emotional adjectives used for the rating scales used in Experiment 2 and 3

The avoidance and approach axes proposed by Harmon-Jones et al., can be visualized as a 45 degree rotation on the arousal-valence dimensions in [Figure 2.1.11](#). Thus, the combination of 'high arousal' and 'high valence' is labelled

'approach' (In green), whereas 'high arousal' and 'low valence' is labelled 'avoidance' (in red).

### 2.1.12. Summary of Electroencephalography

Electroencephalography has a 140 year history and can give a cheap and non-invasive, real-time measure of the complex and rapid information processing of the human brain. EEG is a complex and noisy signal with high temporal resolution and is a useful diagnostic tool for a number of conditions (Kropotov, 2010).

Emotional variations can be indexed by asymmetric activation of the frontal brain regions. As alpha brainwaves are inversely correlated with oxygen consumption, which is the fuel of the brain, they can provide a real-time index of a person's arousal and valence.

As discussed above in section 2.1.2, the real-time presentation of the EEG is useful in **Brain-Computer Interface**, continuous **EEG Monitoring** and **neurofeedback**

## 2.2. A Brief overview of Neurofeedback

**Neurofeedback** was first reported by Joe Kamiya in the 1960s and initially used auditory feedback but with the development of computer graphics in the 80s the sound feedback was relegated to basic triggering of alarm type sounds or effects such as rocket ship engines or guns firing that accompany the graphic display.

Neurofeedback is a specialist sub-set of **Biofeedback** that focuses specifically on brain activity. In the last decade other neuroimaging techniques such as **functional magnetic resonance imaging** (fMRI) (Caria et al., 2007; Lévesque et al., 2006) and **Hemoencephalography** (HEG) (Mize, 2005) have developed neurofeedback systems. Therefore for technical clarity the full title should be Real-Time electroencephalogram neurofeedback but in this dissertation will be referred to as neurofeedback.

### 2.2.1. Subdomains of Neurofeedback

The Society of Applied Neuroscience (SAN) is a European body that represents neurofeedback and classifies neurofeedback into three application areas: **clinical**, **educational** and **peak performance**. There is long-established empirical evidence in the clinical and educational domains with neurofeedback being considered as an effective intervention for conditions such as epilepsy (Stermann, 1972) and ADHD (Arns et al., 2009). More recently, evidence has emerged of the benefits of neurofeedback in the treatment of conditions such as dyslexia (Steffert and Steffert, 2011), sleep (Hoedlmoser et al., 2008), and in a review by (Hammond, 2014) for autism, headaches, anxiety, insomnia, substance abuse, pain disorders and traumatic brain injury.

In the '**peak performance**' domain, the focus is on improving performance that is already within normal bounds. Example applications aim to improve performance in areas such as creativity (Thompson, Steffert, Redding, et al., 2008), sports (Sherlin et al., 2013), dance (Gruzelier et al., 2013) and memory (Vernon et al., 2003).

Within the field of **neurofeedback** there are three subdomains: **Slow cortical potentials** (SCPs), **Alpha/Theta** and **Beta/SMR** or awake state training (where the SMR stands for sensorimotor rhythm).

#### 2.2.1.1. Slow Cortical Potentials

**Slow cortical potentials** (SCP) are very slow amplitude fluctuations of the electrical activity from the upper cortical layer of the brain and have a time range from 0.3 seconds up to several seconds. SCP neurofeedback has been classified, as "possibly efficacious" for ADHD (Strehl, 2009). Although this subdomain of neurofeedback has a strong research history, in order to record this very slow potentials it is necessary to use at DC coupled amplifiers with specialist electrodes which were very expensive until recently, therefore there have not been a lot of clinical applications. As measuring slow cortical potentials requires specialist equipment and a different type of analysis this research will not considered this subdomain.

#### 2.2.1.2. Alpha/Theta

**Alpha/Theta** subdomain of neurofeedback specialises in relaxation and trauma therapies, and has shown some utility and convincing research evidence in post-traumatic stress disorder (Peniston and Kulkosky, 1991), alcoholism (Peniston and Kulkosky, 1989), creativity (Gruzelier et al., 2013) and mood (Raymond et al., 2005).

Alpha/Theta training is usually done with the patient/client reclined in a relaxing setting with the eyes closed. Currently feedback is given by triggering pre-recorded sound files of for example a babbling brook when the Alpha activity is higher than Theta or crashing waves when theta is above alpha. Thus as a

person's arousal changes their theta or alpha will cross an amplitude threshold set by the therapist and different sounds will be played. When short bursts of alpha brain wave activity occurs it is rewarded by playing high-frequency prayer gong type sounds and bursts of theta activity by low-frequency gongs. While the sound is triggered by an EEG event this is more of an alarm than a sonification and fails to reflect the complexity of the brain or the temporal course of arousal state.

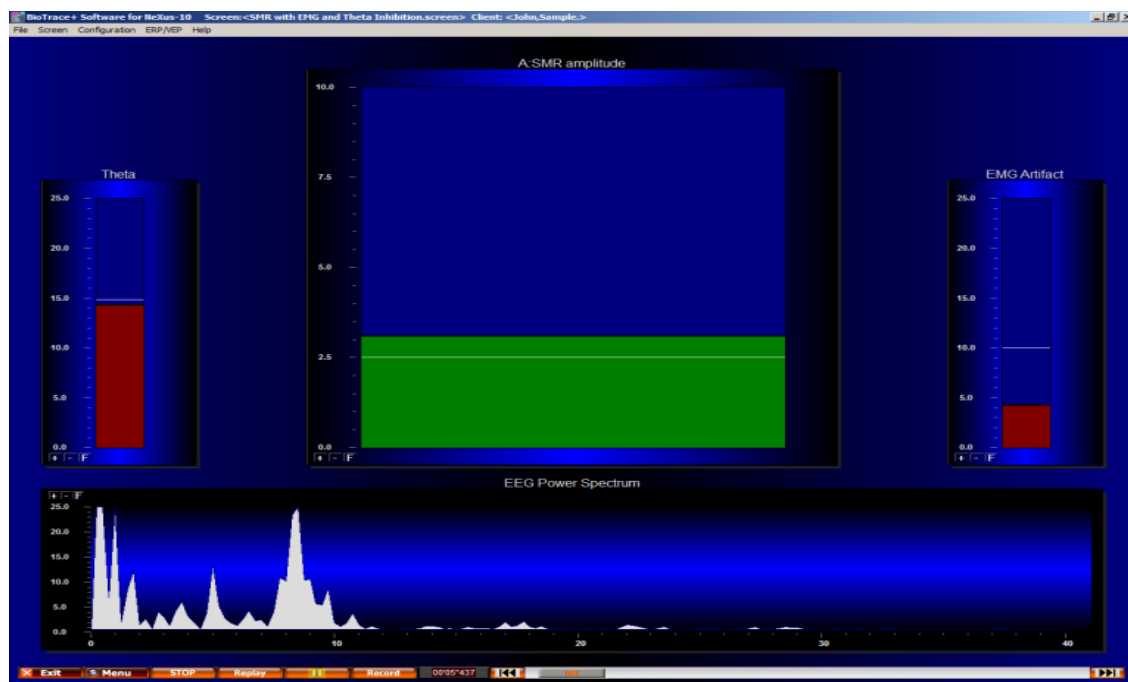
The basic idea behind Alpha/Theta training is to lower the arousal state to the edge of sleep, but not to go into sleep, therefore often referred to as a hypnagogic state. This is suggested to allow access to limbic brain activity where traumatic memories are stored but without triggering the somatic or body fear response, thus allowing therapeutic access to deep traumas without stimulating a fight and flight response (Gruzelier, 2014a).

#### 2.2.1.3. Beta/SMR

The third subdomain of neurofeedback, often called **Beta/SMR**, but this is somewhat of a misnomer because any EEG frequency band could be used including alpha and theta, but the distinction is that the neurofeedback task requires the person to maintain an active brain state during the session and the participant is explicitly trying to modify the chosen EEG parameters, unlike Alpha/Theta training which is aiming to cultivate a 'lack of trying' or a 'letting go' and lowering arousal and increasing relaxation (Gruzelier, 2014b).

The majority of neurofeedback systems since the 1980s displayed the EEG activity on a computer screen and the feedback is given with moving graphic

objects that can increase in size or shrink depending on the amplitude of the chosen EEG band or their colour changes when the reward criterion is met.



**Figure 2.2.1.3:** Shows a typical neurofeedback training screen from the BioTrace software from Mind Media: The three bars are digital filters of Theta on left, 'Low beta' in middle and 'High beta' of right. Below in white is a fast Fourier transform (FFT) spectrogram from 0 to 60 Hz.

A typical example is attention training where the Beta power (15 to 18 Hz) needs to be increased and simultaneously the Theta power (4 to 8 Hz) decreased in the front of the brain (Gruzelier, 2014b). In [figure 2.2.1.3](#) the three bars on the screen represent brain activity, on the left is the Theta band that is associated with low arousal and should be decreased or inhibited. On the right is 'High frequency Beta' (18 to 25 Hz) which is associated with over arousal and muscle activity and should also be decreased. In the middle is the 'Low Beta'

band and is the main activity that needs to be increased or rewarded. When the two inhibit bands of Theta and High Beta are below a threshold set by the therapist **and** at the same time 'Low beta' is above the threshold, then the person will receive a reward by achieving points or hearing a beep, which is usually associated with some praise from the therapist.

The same principle can be used to stop and start a film or animation, where the film playing is the reward. These game-like displays, where the EEG controls the behaviour of the game, help to make the training more interesting and maintain motivation.

### 2.2.2. Numbers & Duration of Sessions

Neurofeedback generally requires between 10 and 40 training sessions of around 20 to 40 minutes each to make a lasting change in symptoms or physiology (Hammond, 2007) and it is commonly believed in the field that people do not have a sense of control or knowing what to do, for at least 5 or 6 sessions of neurofeedback. But as will be shown in the literature review in [chapter 3](#), there are some research paradigms that have shown changes in physiology or psychometric measures in just one session.

### 2.2.3. Learning, Conditioning & Reward Delay

Learning is a more or less permanent change as a result of experience and can change the strength of connections between participating neurons that have been activated or 'conditioned' by a stimulus. The stimulus propagates an electrical charge that precipitates protein synthesis. There are two stages to this process; the first stage is short term conscious memory which depends on reverberating activity in cortical nerve circuits (Hebb, 1949). The second stage is



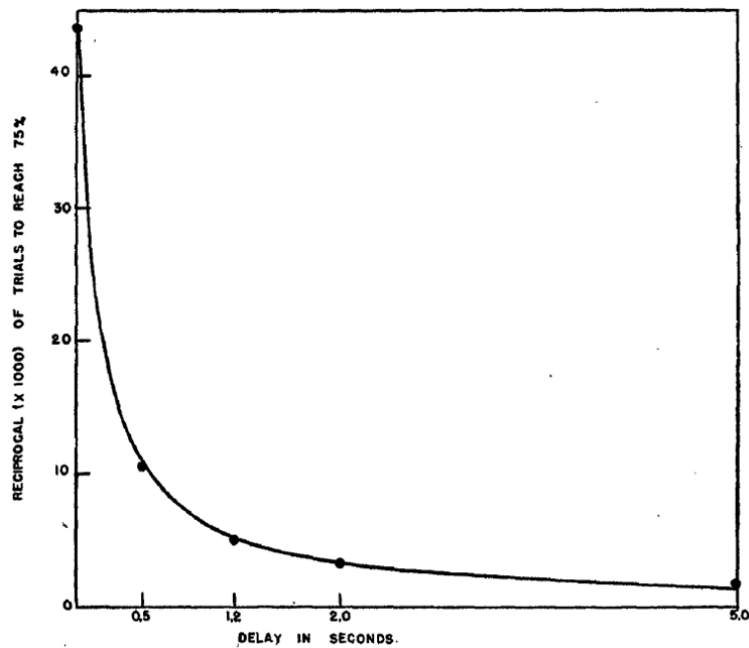
transfer of these signals to the hippocampus which starts the process of long term storage or long-term potentiation (LTP) that results in a permanent change in the distribution of cortical networks (Lashley, 1930). When an organism experiences a reinforcing stimulus, neurotransmitter pathways in the brain are activated and new synapses are made or strengthened that can last a lifetime. This is believed to be the basis of all learning and memory from sea-slugs (Abrams and Kandel, 1988), to humans (Pithers, 1985).

**Ivan Pavlov** the famous Russian physiologist and Nobel laureate demonstrated **classical conditioning** in dogs that heard a bell before they were given their food and were later found to salivate simply to the sound of the bell even when no food arrived. The bell was called the conditioned stimulus (CS) because it needed to be learned and the food unconditioned stimulus (US) because the dog already knows what food is (Pavlov, 1927).

**B.F. Skinner** went on to demonstrate a different type of learning called **operant conditioning**, where a reward is contingent on the actions of the animal, so that the experimenter would wait for a predefined behaviour to occur and when the organism meets the criterion a reward was given. Skinner claimed almost all human learning was based on operant conditioning and that individuals do what they are rewarded for doing (Skinner 1938; 1950).

Conditioning depends on learning the temporal intervals between stimulus and the reward and there are four important factors in operant conditioning that will affect the impact of both the stimulus and reward; **Immediacy**, **Contingency**, **Satiation** and **Saliency**. When the time between the response

and the reinforcement is increased, called 'reinforcement delay', the learning efficiency will decrease (Grice, 1948).



**Figure 2.2.3.1:** Rate of learning as a function of delay reward. The reciprocal x 1000 of the number of trials to reach a level of 75% correct choices is plotted against time of delay. Experimental values are represented by Black dots and smoothed curve is fitted to these data (Grice, 1948).

**Figure 2.2.3.1** shows a typical example of the impact on learning of different reinforcement delays in a study of mice learning a colour discrimination task with a food reward. The line shows that as the delay is increased the number of trials needed to learn the correct response increases at a logarithmic rate and for Mice a delay of more than 30 seconds typically stops them from learning the task (Grice, 1948).

These mechanisms are believed to be important for humans as well as mice, for learning in neurofeedback. Professor Barry Sterman was one of the early pioneers in the field of neurofeedback with his first studies in the 1960s. He was a sleep researcher and was investigating the neural mechanisms of sleep onset. In recording the EEG from cats at Cz on the top of the head, (see [section 2.1.5.1](#)), he noticed that when a cat was sitting still and concentrating, it produced an increase in EEG activity in the 12 to 15 Hz range on the sensory motor strip, which he named sensory motor rhythm (SMR).

Sterman wished to see if he could operantly condition this activity, so he reduced the food given to the cats to produce slightly hungry animals and put them in a small cage with a glass window. When the cats produced more of the SMR activity a light indicated to the cat that it had performed the task. Then the window would open and the cats could eat a small portion of chicken soup and this procedure was repeated until the cats were satiated. Sterman was able to show that with this operant conditioning paradigm, the cats could be trained to modify the EEG activity.

In a second unrelated chemical toxicity experiment to establish a dose response curve of a toxic rocket fuel, some of the cats that had been trained to increase their SMR were inadvertently mixed in with some untrained cats. Sterman discovered that the cats that had completed the neurofeedback training had a raised threshold to the toxin and took an average of twice as long before having a toxin induced seizure as well as having a reduction in mortality rates. Exactly how the neurofeedback training increase the cat's tolerance to the toxin is still unclear, but it seems that the firing threshold of the

neurones was raised by a general deactivation of the system (Stermán and Egnér, 2006).

In follow-up studies at first with cats in the Lab and later on humans with drug-resistant epilepsy on a waiting list for radical brain surgery to remove the brain region with the seizure activity, Stermán showed that the SMR neurofeedback training could reduce epileptic seizure prevalence (Stermán, 2000). Stermán concluded that the efficacy of the neurofeedback depended on the delay being less than 200 milliseconds (Stermán, personal communication 2002).

Therefore, with operant conditioning and consequently neurofeedback, the more **Immediate**, **Contingent**, and **Salient** the reward, the quicker the learning is likely to be.

#### 2.2.4.      **Immediacy, Smoothing and Delay**

There are a number of complex and technical issues that affect the time delay between the EEG event and the reward stimulus. Unfortunately this issue of the immediacy of reward in neurofeedback is an underappreciated and under reported problem and only a handful of papers report any details on how the filters, and smoothing of the display graphics are set.

One critical issue is how the power of the EEG signal is computed and displayed, as different computational methods can introduce different amounts of time delay.

For example a very common way to compute a band power from the raw EEG is to use a mathematical method called the 'fast Fourier transform' to transform the time series data into the frequency domain. This technique uses a

windowing method to average the frequency over a set duration which for EEG is usually around 1 to 4 seconds and the longer the time window the more accurate the frequency resolution but the greater the delay between the EEG event and the output of the algorithm (Cacioppo et al., 2007, p. 65).

Secondly with a visual display for example, where a bar graph represents an EEG parameter, the moving up and down of the bar can be too rapid for the eyes to track the activity. Therefore it is quite common to add some smoothing or data averaging to slow the display and reduce eye strain.

But both of these examples can introduce delays that could inhibit learning on the neurofeedback task.

In a presentation at the Society of Applied Neuroscience (SAN) conference in 2014, **van Beek** made the same observation, saying that

“Averaging the EEG signal during neurofeedback will smooth the signal which could be more pleasant for subjects in terms of fewer feedback interruptions. However, it is unknown to what extent the contingency with the actual EEG signal decreases due to the increase of the duration of the period over which the signal is averaged.” (van Beek and Breteler, 2014)

van Beek computed a number of different averaging durations with thresholds for different percentages and concluded,

“Longer periods over which the signal was averaged corresponded with less contingency with the actual EEG signal. Furthermore, with higher reward percentages (i.e. by lowering the amplitude threshold of reward for an EEG signal, so that it meets the trained criterion for a greater percentage of time)

the feedback dynamics were more comparable to a random signal generator".

As discussed in [section 2.3](#) below, because of the rapid and temporal nature of sound, sonification of EEG could circumvent some of these issues but this is clearly an empirical question.

### 2.2.5. Summary of Neurofeedback

Neurofeedback is a therapeutic brain training intervention with a 60 year history and some very promising research results in a wide range of **clinical**, **educational** and **peak performance** application areas.

Neurofeedback is generally believed to be based on operant conditioning where the **Immediacy**, **Contingency** and **Saliency** of the feedback are critical factors. The training generally takes many sessions and therefore anything that could improve the efficiency of the feedback and learning, would greatly improve learning outcomes and could reduce the number of sessions needed to make a change in physiology all symptoms..

## 2.3. Sonification: Definition and Motivation

According to the International Community for Auditory Display (ICAD) sonification is "The use of non-speech audio to convey information; more specifically sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation" (Kramer et al., 1999, P2.).

Alberto de Campo (2007) proposes two broad subdivisions of auditory displays. The first refers to "Auditory Information Display" that is suited to presenting "well understood data" to communicate discrete information events through alarms and verbal warnings. The second, "Data Sonification", refers to a more information-rich sonic stream particularly appropriate to data exploration.

### **2.3.1. Necessary and sufficient conditions for Sonification**

Thomas Hermann, in 'Taxonomy and Definitions for Sonification and Auditory Display' (Hermann, 2008, p. 1), proposes the "necessary and sufficient conditions for organized sound to be called sonification":

"**(C1)**: The sound reflects objective properties or relations in the input data."

"**(C2)**: The transformation is systematic. This means that there is a precise definition provided of how the data (and optional interactions) cause the sound to change."

"**(C3)**: The sonification is reproducible: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical."

"**(C4)**: The system can intentionally be used with different data, and also be used in repetition with the same data."

But there is a critical constraint missing from these definitions, so for example, the first condition, that the sound reflects objective properties in the input data, is important but leaves much room for interpretation, e.g. which properties, how many and how quickly. It is also questionable whether Herman's conditions really are sufficient: for example, they do not appear to rule out: a sonification

with an output that is beyond human perception or that presents too much data to comprehend, or that presents the data too quickly or slowly to find useful, or is just too uncomfortable to listen to, or is otherwise unlistenable.

Therefore an important caveat to these definitions and conditions is how the sonification will be assessed and against which criteria. In the artistic domain it may be sufficient for an artist to merely affirm satisfaction or for the audience to say they liked it, whereas in the scientific domain more rigorous and quantitative outcome measures would be required.

Thus, the requirements for evidence of suitability can vary considerably between sonifications primarily designed for aesthetic purposes and those more concerned with the fidelity of the data transformation. This distinction becomes critical when it comes to how to assess or validate a sonification's output.

### **2.3.2. Strengths of Sonifications for EEG Neurofeedback**

As has been shown above, the brain is a very complex organ and the EEG data derived from it, is a rich and complex source of information about the brain's activity. The premise of neurofeedback is that if a person is given a suitable real-time presentation of their own EEG data, they can learn to perceive, comprehend and then modify their own brain activity.

Thus this next section will speculate on nine properties of the human auditory system and the way the brain processes sound, as well as some general properties of human cognition, which suggest the sonic display of real-time EEG data in neurofeedback could be potentially useful and provides the motivation for this research.



This background information will inform the design decisions for both the type of sonification techniques that could be used in neurofeedback in this research, as well as informing the research design and assessment methodologies.

### **2.3.3. Eyes Closed or Busy**

One simple and clear advantage sonification offers to the presentation of EEG data is the freeing of the eyes from having to look at a display screen. There are numerous applications such as driving or operating complex equipment, where the user cannot afford to take their eyes from the task but could benefit from more information about their own physiological state.

A second situation is where there is some sort of visual occlusion, either because the eyes are closed, in the dark, where the user is blind, or where there is no direct line of sight to the data display device.

Sonification can provide rich and complex feedback in these situations (Crawford et al., 2002) as the human auditory system can easily perceive and localise a sound source from any angle without having to turn the head.

In the realms of personal physiological monitoring for example, sonification could deliver continuous unobtrusive feedback through standard or bone conductive headphones, allowing the user to freely interact with the environment without being encumbered by visual display devices, thus making physiological monitoring available to wearable applications.

In the neurofeedback domain (see [section 2.2](#)) there are two obvious applications that sonification could facilitate. The first is a "Commuting-Trainer", for users of trains and other forms of public transport, that enables a person

using a mobile EEG system and sonification to unobtrusively or covertly hear continuous real-time feedback of their brain waves through headphones whilst commuting. So, for example, in order to achieve an optimal level of arousal for a coming task, in the morning on the way to work people could train to increase their attention and arousal, whereas on the train home after work, they could train to increase the relaxation and de-stress from the day.

Given the large number of sessions generally required for successful neurofeedback, one difficulty neurofeedback practitioner's face is how to schedule regular multiple sessions of neurofeedback into people's busy lives. A sonified commuter-friendly system could transform otherwise wasted commuting time into useful training sessions.

A further use case in which sonification could facilitate neurofeedback is in what is known as Alpha/Theta training. Alpha/Theta neurofeedback is an established therapeutic branch of neurofeedback that specialises in relaxation and trauma therapy and is generally performed reclining in a relaxing setting with the eyes closed. (See [section 2.2.1.2](#) above for a more detailed explanation of Alpha/Theta neurofeedback).

#### **2.3.4. Temporal Resolution - Eyes, Ears and Brain**

Sound, and therefore the human auditory system, is distinctively temporal in nature (Neuhoff, 2011, p. 74) with high temporal resolution auditory signals being processed in the left auditory cortex in humans (Liégeois-Chauvel et al., 1999), whereas the visual system is primarily spatial (Kozhevnikov et al., 2005). This has implications for processing speed and reaction times - which may have implications for the immediacy of the feedback signal, as will now be explored.

In the human brain, information from the eyes is subdivided into slow and fast information processing streams, known as the "what" and the "where" pathways (Goodale and Milner, 1992). Visual information from both pathways is sent from the eyes to an area in the back of the brain called the 'primary visual cortex'.

The "what" pathway is called the parvocellular pathway and is responsible for the slower processing of "what" things are. For example the task of facial recognition is carried out in the ventral stream on the right side of the brain which process visual information from the parvocellular pathway.

On the other hand, the "where" pathway is called the magnocellular pathway and is responsible for the fast processing of "where" things are in space. Visual information from the magnocellular pathway is processed in the dorsal stream that runs up the back of the middle of the brain and sends information to the motor cortex, which controls movements, such as where to look.

By contrast, the human auditory cortex is in the temporal lobes just above the ears. An acoustic stimulus reaches the brain at around 80 ms, as compared to 120 ms for a visual stimulus to reach the visual cortex (Ward, 2010). Most people have a quicker reaction time to an acoustic stimulus compared to a visual one and the "Mean reaction time for college-age individuals is about 160 milliseconds to detect an auditory stimulus, and approximately 190 milliseconds to detect a visual stimulus" (Kosinski, 2008).

According to Resnick & Feth (1975), "Investigations of auditory temporal resolution typically have yielded estimates of a 'temporal threshold' on the order of 2 ms". By contrast in the human visual system, the flicker fusion

threshold is the rate at which a flashing light will appear as “constantly on”, is around 60 Hz or 16.6 ms per cycle. So for example a projected film has a frame rate of 24 frames per second, or 42 ms per frame and a computer monitor has a frame rate of 50 Hz or 20ms per cycle, limiting the speed at which visual information can be displayed to tens of milliseconds.

Given the above, it could be argued that sonification has a possible temporal advantage over visual display in the form of lower latency, with the potential for the gap between actions and feedback to be reduced.

As was discussed in [sections 2.1.3](#) and [2.2.3](#), EEG has the fastest temporal resolution of the neuroimaging techniques. Consequently, other things being equal, from the perspective of operant conditioning learning theory, neurofeedback should benefit from the more rapid presentation of the activity being trained.

### **2.3.5. Temporal Dynamics - Rhythm Perception**

The human auditory system is sensitive to acoustic events over a range of different time scales. For example, the **frequency response** of the human ear is typically given as 20 Hz to 20,000 Hz (Ward, 2010), whereas the useful **pitch perception** range is closer to 30 to 5,000 Hz (Wier et al., 1977). This follows partly from the fact that the Just Noticeable Difference (JND) of pitch greatly increases above 5 KHz. On a different time scale, **beat perception** is most sensitive in the frequency range around 0.5 - 5 Hz (or 30 - 300 beats per minute). Within this range, repeated acoustic events can be heard individually and are generally judged to be rhythmical in character. (Snyder, 2000)

Snyder suggests that “When two or more events take place within the length of short-term memory” which is around three to five seconds, they will be perceived as rhythm. If a regular acoustic event is faster than around 16 events per second then it starts to “fuse” and be perceived as a single sound with a pitch, whereas if there is less than one event every 8 seconds, the sounds will be heard as individual events.

The Human beat perception range of 0.5 - 5 Hz is a very useful temporal range for the presentation of EEG data. Although 98% of all EEG power is in the frequency range 0 to 30 Hz (Kropotov, 2010) and this is below the human auditory frequency response, the amplitude envelope, or waxing and waning, of the power of the different frequency bands of the EEG has activity within human beat perception range. So for example the characteristic fluctuations of alpha power, called alpha spindles, that vary with a person's arousal levels, fatigue and drowsiness, typically happen over a time scale of between 0.5 to 2 seconds (Lawhern et al., 2013). This means that sonification of EEG Alpha spindles that followed the amplitude envelope, for example, would generate rhythmic sounds at a typical music-like rate and the temporal dynamics of the EEG data could have a temporal similarity to the rhythmic structure of music. Given that most people have considerable familiarity, via music, of attending to rhythmic detail on this temporal scale, this suggests that sonification could be well suited to supporting the presentation and perception of the fine and complex temporal dynamics of the EEG signal.

#### **2.3.6. Multiple streams and the cocktail party effect**

A powerful property of the human auditory system is known as the cocktail party effect (Pollack and Pickett, 1957). This is the ability to focus on one

acoustic stream of information within a complex soundscape and filter out irrelevant distractions. For example, in a crowded and noisy room it is usually possible to focus on a single conversation and ignore others. Furthermore if your name is called out from behind you, it is typically possible to orient and focus one's attention on the new sound stream. The apparent effortlessness of this task belies its complexity.

This is a potentially useful property for the presentation of EEG data, since, just as in a cocktail party, EEG has multiple channels of complex time series data with multiple sub components of each channel that represent activities in different parts of the brain (Kropotov, 2010).

The ability of people to focus their attention selectively within multiple streams of sound and to perform complex spatio-temporal decomposition in a cocktail party, in order to attend to a single speaker, suggests that people may be able to do exactly the same trick with EEG sonification, in order to distinguish between different components of brain activity.

### **2.3.7. Cognitive Congruence, Cognitive Load & Perceptual Redundancy**

Whether analysing a pre-recorded multichannel EEG for diagnostic purposes or tracking a single EEG channel in real-time for training purposes, EEG analysis is a complex task that generally requires cognitive effort. The goal of neurofeedback is to train a participant's ability to control their own EEG activity, rather than training a participant to become an EEG expert. Therefore anything that could reduce the cognitive effort of the task might be expected to increase learning efficiency and improve motivation.

John Sweller in his 'Cognitive Load Theory' (1988) suggests that because short term memory has a very limited capacity (Miller, 1956), information processing is carried out using schemas held in long term memory. According to Sweller, the difference between an expert and a novice is that a novice hasn't acquired the schemas of an expert. Furthermore, he argues that the learning of the schemas happens best under conditions that are aligned with human cognitive architecture. In other words if new incoming information is presented in a manner that matches the nature of the knowledge, the new data is easier to comprehend. This suggests that **spatial** information is best presented in a **spatial mode**. So for example it is possible to give a verbal description of a spatial object like a "square" but a spatial description, such as a picture of a square, is more efficient. Sweller says "From an instructional perspective, information contained in instructional material must first be processed by working memory. For schema acquisition to occur, instruction should be designed to reduce working memory load". Sweller suggests that some tasks require so much cognitive effort to perform that they do not leave sufficient mental capacity for the development of a new schema, meaning that expertise is difficult to achieve. This suggests that reducing the cognitive demands of a complex task would free up capacity to develop the cognitive schemas and make skill acquisition more efficient.

The real-time presentation of EEG and sound are both fundamentally temporal in nature; EEG is the sum of multiple different amplitude fluctuations in multiple frequency bands from a myriad of neural networks. Likewise a sound scape is made up of a myriad of sound components. Accordingly, presenting time series EEG data as a temporally congruent sound stream could help to lower the

cognitive effort required to extract relevant features from the complex and noisy EEG signal. Or, as Flowers (2005) points out more succinctly "Something that works, is using time to represent time".

There are two complementary approaches to increase perceptual redundancy whilst retaining temporal congruence when sonifying time series data. The first of these approaches is discussed by Neuhoff in chapter 4 of the sonification handbook (Neuhoff, 2011) and is called 'redundant mapping'. This is where a single data property is mapped to multiple sound features such as pitch and loudness. Peres and Lane (2005) showed that this improved performance for the specific activity of monitoring an audio box plot while performing a simultaneous visual task. The suggestion is that such redundant mapping strategies increase perceptual redundancy and therefore lead to a reduction in cognitive workload thus making learning more efficient.

The second of these approaches is to sonify multiple features of the same data property. So, for example presenting multiple sound streams of statistical properties (such as the mean, standard deviation, skewness, kurtosis, maxima and minima or short and long range averages) from the same dataset. In a contrasting way from the first approach, this could provide overlapping or potentially redundant information and make the task of detecting the signal in a noisy background less effortful.

An example of this second approach in the neurofeedback domain would be relaxation training (Gruzelier, 2014b), where with a visual display it is typical to display a broadband alpha frequency range of 8 to 12 hertz, as a single stream



of information, as it can be confusing for the eyes to try and track multiple visual stimuli.

However it would be easy to create a sonification that could present four individual 1 Hz bands of information from 8 to 12 hertz in real-time (Hermann et al., 2002), (See: Spectral mapping: in A2.4 Sonification Techniques). This is a tantalising prospect that would need to be tested to see if people could focus on the most relevant stream at any one time or could they synthesise the 5 EEG bands into a single stream and whether this approach could convey more information in a way that facilitated comprehension.

### **2.3.8. The Practice Effect**

The adage 'practice makes perfect' applies to the use of both sonification and neurofeedback, in that both the task of making sense of a sonic representation of data and the task of understanding a real-time representation of one's own brain waves require an initial stage of learning. For both tasks, in the initial stage of learning, the cognitive load can be high and the learning objectives can be unclear. Thus as Sweller pointed out above, if the learning phase of a task is too demanding, there may not be spare cognitive capacity to develop the schemas needed to achieve competency or automaticity. In general terms, the more complex a task or an interface, the longer it takes to achieve confidence and the greater the impact of practice but the greater the range of control or utility.

So for example, as someone repeatedly listens to the same sound, they become able to hear more detail and can identify salient features more rapidly and accurately, for example, a skilled mechanic diagnosing a fault from a

subtle change in the sound of an engine. A complex sonification that presents more information might take longer to learn but once skill has been developed, it could have the potential to allow better perception and performance.

### **2.3.9. Auditory Gestalt and Meaning-Making**

Gestalt perception is the mental task of comprehending an object as a whole, as opposed to the single elements that make up the object. This term relates to the idea that we jump directly to the perception of an object and that we do not consciously perceive the process of constructing what we perceive from its elements.

For example, when presented with novel complex random noises, people will typically ascribe a meaning and label the sound semantically, they are unlikely to characterise the sound technically, by saying things like "It is a low frequency repeating pattern" or "It is a high frequency noise with a fast attack". People are far more likely to say things like "It sounds like a footstep" or "a glass breaking". (Handel, 1995).

This is a powerful and useful property of the perceptual system, on which sonification can capitalise. If a sonification strategy can aid the creation of perceptual gestalts, this has the potential to turn a complex task of focusing on multiple features of the data into the single task of monitoring a single gestalt and this could improve performance in detecting the signal (Schmitz et al., 2013). This could be useful when trying to use EEG to monitor one's cognitive or emotional state.

Furthermore as Serafin suggests in Chapter 5 of The Sonification Handbook;

"Sound can lead to characteristic sonic interaction gestalts which allow us to compare repeated instances of interactions. For instance, the sound of a gait becomes a pattern from which a person can be identified. For sonification of body movements, a complex movement such as a pirouette in dance or a racket serve in tennis may be turned into a sonic contour which can be compared to an ideal movement execution in timing and expression" (Serafin et al., 2011). This could help to develop perceptual expertise in the complex temporal pattern matching task of neurofeedback.

#### **2.3.10. Embodied Cognition and Peripersonal Space**

One speculative but exciting possibility sonification could offer to EEG neurofeedback is increasing the feelings of embodied cognition (Birbaumer et al., 2013; Wilson and Foglia, 2011).

With the visual display of brain waves in neurofeedback the brain activity which is a measure of a person's internal state is externalised and happens at a distance from the person on a computer screen. The task is to try and associate the movement of a bar or rocket ship on the screen with the mental activity that evoked the movement. But this could create a distance between the internal behaviour of the person and the activity on the monitor, potentially creating some cognitive dissonance and increasing workload.

There is a growing body of evidence that suggests that many cognitive processes are inextricably linked to the motor function that accompanies them and when a mental and physical task is congruent, performance in the mental task is more efficient (Wilson and Foglia, 2011).

The brain has several different areas that process space according to where it is in relation to the body. The space that is within the grasp is called peripersonal space and is processed in the parietal lobe in the back of the brain. Extrapersonal space is the region beyond the reach and is handled in the temporal lobe on the side of the brain. Pericutaneous space is the region just outside the body but where an object could touch (di Pellegrino and Làdavas, 2015).

For example, in stroke victims with visual neglect because of damage to the parietal lobe, sometimes they cannot see anything in their peripersonal space but can see objects in extrapersonal space that is beyond their reach. Disconcertingly when they are given a stick to touch the object they can see, the object would disappear, as it is now within reach, so the visual processing is switched to the damaged peripersonal region (Ward, 2010).

Unlike Seismological or stock market data the unique and significant feature of the real-time EEG data in the neurofeedback loop is that the data is created by the person that is simultaneously listening to the data stream and trying to modify the behaviour that created the data.

So when the brain activity is turned into sound the activity could be perceived as happening inside the head close to where it is being generated. Internalising the data presentation in a way that is not possible with a visual domain, this could increase the feelings of embodied cognition and aid learning by making neurofeedback more of a feeling task than a thinking task.

### 2.3.11. Sound, Music and Motivation

Salimpoor (Salimpoor et al., 2015, p. 1) suggests that “Music is essentially a sequence of sounds organized through time...” and “the temporal dimension is key to understanding how music exerts its powerful affective impact”.

The sonification of the EEG creates a rich and complex sonic output that is also sound organized through time and with the appropriate sonification technique the EEG could be heard as music. Thus given that all cultures have valued music and the vast majority of people like or even crave music (Salimpoor et al., 2015) and only around 4% of the population have congenital amusia and do not appreciate music, (Peretz and Hyde 2003).

Thus if a sonification can be made to produce a musical like sound output then it can capitalise on the power of music and create an intrinsically rewarding display of the EEG data.

But it is more than just the temporal similarity between sound and EEG that could prove advantageous. Music and sound have an affective quality that could be exploited to convey meaning. So for example if the affective state of a participant could be converted into an acoustic signal that is cognitively congruent with the affective meaning of the sound, referencing all the learned affective associations with musical motifs, then cognitive load would be reduced and learning efficiency would increase.

Wu (2010) for example, sonified the EEG of slow-wave sleep (this is deep sleep) and rapid-eye movement sleep (REM) (is dreaming sleep) and found that slow-wave sleep sounded slow and relaxing whereas REM sounded much more

active. The sounds of the sonification were congruent with the activation levels of the two sleep states.

Therefore by converting EEG into sound, EEG sonification could harness the cognitive schemas for music processing, that we have all spent a lifetime mastering. Not only would this give the ear an advantage over the eye but would enable the mind to grasp the complex structure of EEG more easily than current visual feedback methods.

Furthermore with neurofeedback there is generally a desired goal state that the training is trying to achieve. So for example, training may focus on increasing the amount of the relaxing alpha brain waves to reduce stress or decreasing the theta brain waves that are associated with under arousal to increase concentration. Thus it could be possible to 'tune' a sonification output so that as the physiological activity moved towards the desired goal, the sound output of the sonification could sound more musical or less dissonant for example.

This could create an intuitive and rewarding feedback modality, were the direction of the goal state does not require explanation from the therapist and is easy to remember.

A major problem for neurofeedback is maintaining motivation across multiple sessions, particularly before the person has learnt to control the physiological parameter or seen any improvements in their symptoms. So a 'music like' representation of a person's brain waves could greatly improve motivation and therefore learning outcomes.

Making the "sound of the brain" music to the ear!

### 2.3.12. Summary of Sonification

To summarise, the potential advantages that sonification can offer to neurofeedback for the presentation of EEG are mostly due to the capacity of the human auditory system to derive meaning from complex and rapid audio streams. Coupled with, the similarity between the temporal dynamics of the natural soundscape that humans have evolved to comprehend and the sonic output of an EEG sonification.

One principal advantage the auditory presentation of EEG has over a visual display is its **temporal resolution**. The brain may produce in the region of  $8.6 \times 10^{15}$  action potentials per second and EEG can measure the sum of this activation at 500 Hz, creating a temporally complex and rapid data stream. Thus the primary bottle neck of information transfer in neurofeedback can be the perceptual ability of a person to comprehend this rapid signal. Thus the use of sound to convey EEG could potentially capitalise on the human auditory systems faster temporal resolution.

A second potential benefit is that the temporal dynamics of many salient EEG parameters fit neatly within the range of the human auditory systems **rhythm perception** and this means the sonification of the EEG for neurofeedback can capitalise on the millennia of evolution that has honed the human auditory systems ability to perceive and track complex rhythmical acoustic events in a noisy soundscape.

A third advantage is the apparent effortlessness of the “**cocktail party effect**” and how the auditory system is able to perform complex **temporal/spatial filtering** and detection on **multiple streams** of sound. In many ways the EEG

signal is similar to a noisy cocktail party, there are many different sources of information in a noisy background and the problem for the trainee when trying to learn to modify their physiology with neurofeedback is working out which data stream to focus on.

Two more useful psychoacoustic properties of the human auditory system are its ability to automatically categorize acoustic features into a meaningful **auditory Gestalt** and derive pleasure from complex rhythmic sonic patterns called music.

Sonification faces a number of hurdles to be accepted as a useful tool in the display of EEG. One issue that may well have inhibited research into sonification, is the oculocentric nature of science, that favours visual displays (Mody, 2005).

Alexandra Supper (Supper, 2012), suggests that sonification is in search of the “killer app”, or more correctly in search of a field that would find sonification their killer app. Something that will make people realise sonification's true potential, equivalent to how the geological sciences championed the visualisation of data in the early 19th century.

This may well be true but on the other hand what this “killer app” type of ‘quick fix’ thinking fails to understand is that, science is not just a matter of finding a killer app or someone who needs a novel tool. A scientific discipline is based on decades of carefully designed and meticulously implemented empirical studies. Evidence that people can understand and trust, with findings built up from many labs over many studies. But as will be shown in the next chapter this is what is missing in the field of EEG sonification.



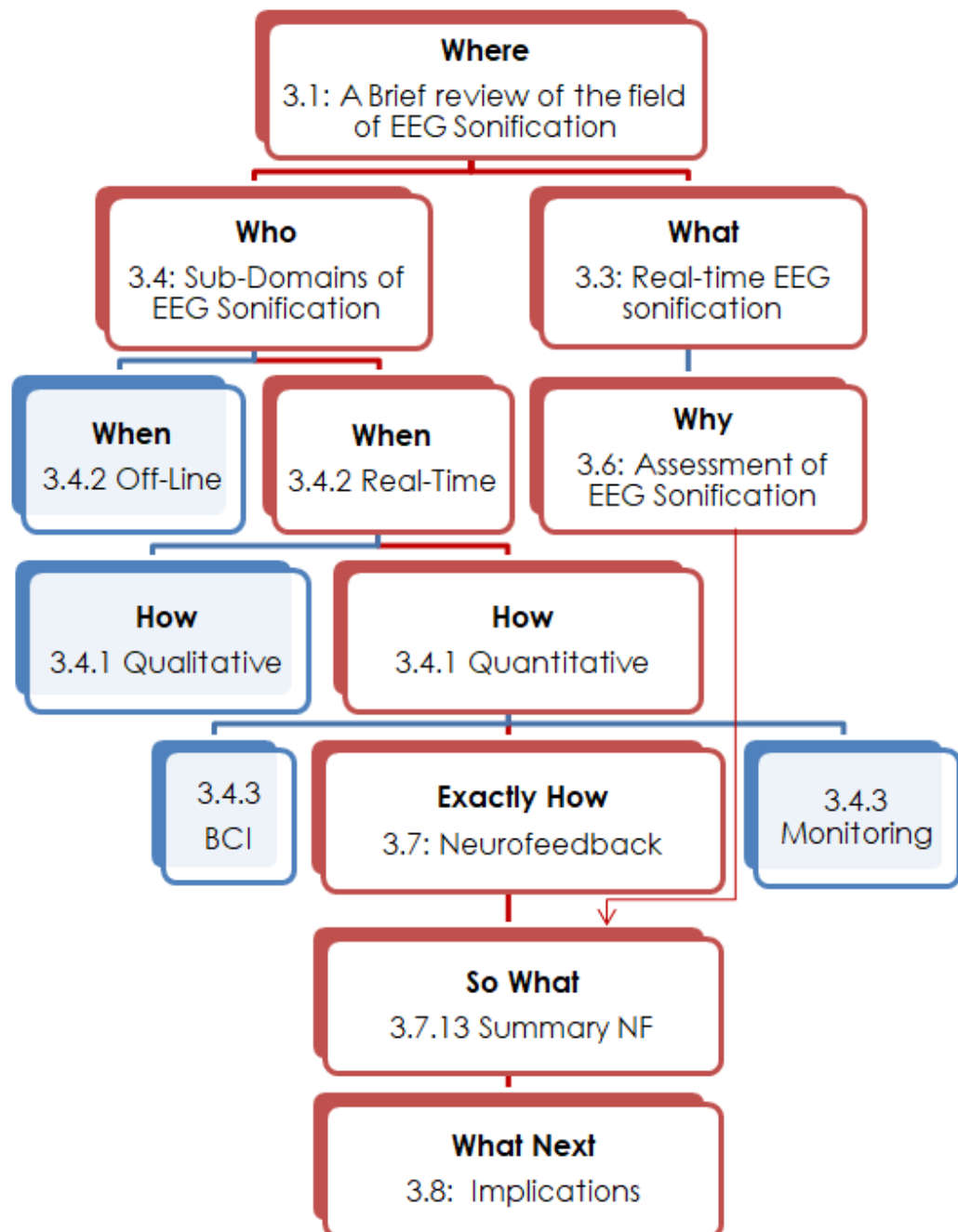
Neurofeedback is a field that needs better presentations of complex time series data and as hopefully has been shown above; sonification can provide many useful properties for the real-time display of EEG data.

This dissertation will explore the idea that sonification could be a useful tool for the display of EEG for neurofeedback. Because the sonification of the EEG signal could allow the full complexity of the multivariate time series EEG data stream of the brain to be transmitted accurately with high temporal resolution in real-time to the human auditory system. In a manner that can be intrinsically rewarding and which could capitalise on the strengths of the human auditory system to derive meaning from complex time series data.

Thus sonification could be neurofeedback's "killer app" and neurofeedback could be the field to champion sonification.

This chapter was a brief overview of some of the important domains that will be referred to in this research and the next chapter will present a literature review of the EEG sonification and neurofeedback research.

## Chapter 3: Review of the Research field of EEG Sonification



**Figure 3.1:** Shows a schematic of the sections in this chapter

### 3.1. Introduction

After a brief introduction to the history of EEG sonification, this chapter classifies all publications on EEG sonification found in a systematic survey. Applications of EEG are broken into categories, and key distinctions are made between the various uses.

The literature review then moves to sonification, and different sonification techniques are compared: in particular criteria are considered for selecting sonification methods for EEG applications. Approaches to assessing EEG sonifications are considered. Finally, all papers on neurofeedback sonification found in the survey are reviewed, and implications considered.

### 3.2. History of EEG Sonification

In 1934, only 5 years after the neurologist Hans Berger first published his invention of the electroencephalograph (EEG), the Nobel laureate Prof. Edgar Adrian of Cambridge University reported the sonification of his own EEG in the journal *Brain*, (Adrian and Matthews, 1934) by playing his EEG through a telephone. Since then many physiological parameters of the human body have been sonified, such as, Heart Rate Variability (**HRV**) (Ballora et al., 2004); Blood Oxygen saturation (Janata and Edwards, 2012); Respiration (Watson et al., 2004); Electromyogram (**EMG**), i.e. the electrical activity of muscles (Pauletto and Hunt, 2006); Electrooculogram (**EOG**), i.e. the electrical activity of the eye (Arslan et al., 2005); and Galvanic Skin Response (**GSR**) the electrical resistance of the skin (Kosunen et al., 2010).

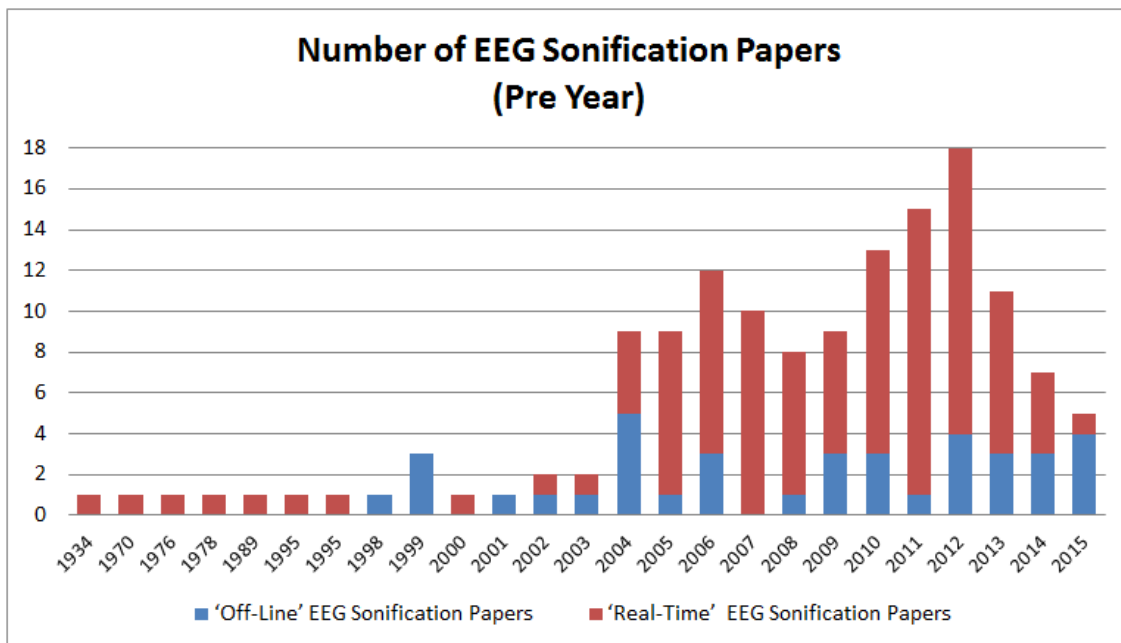
Several brain imaging techniques, have been sonified in the last 83 years, including: functional Magnetic Resonance Imaging (**fMRI**) (Schmele and Gomez, 2012); Positron emission tomography (**PET**) (Rogińska et al., 2013); Magnetoencephalography (**MEG**) (Dumas et al., 2011); imaging techniques associated with the Human Connectome Project (**HCP**), the map of neural connections in the brain (Papachristodoulou et al., 2014); and Electrocorticography (**ECoG**), electrical activity measured from the exposed surface of the brain (Terasawa et al., 2012).

But for the reasons highlighted in the introductory chapter, this research and literature survey will focus exclusively on the sonification of the non-invasive scalp electroencephalogram (**EEG**).

### 3.3. A review of the Research field of EEG Sonification

A brief survey of the field of EEG Sonification has revealed 145 papers, of which 80 (55%) are conference papers (See [Appendix A2.1](#), for a full list) and 57 (39%) are journal papers (See [Appendix A2.2](#)). There were also 7 books or book chapters found on EEG sonification. Of all of the papers, only 12 (8%) were listed in Science direct and PubMed. They were published in 48 different journals ranging in topics from Neuroscience Gerontology, and Medicine to Computer science, data analysis and Music. Of the 80 conference papers, 19 (23%) were presented at the International Conference on Auditory Display (ICAD), 7 (9%) at New Interfaces for Musical Expression (NIME), 5 in International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS), 4 in International Computer Music Conference (ICMC) and only 2 at the conference for Human-

Computer Interaction (CHI). The papers were presented at 42 different conferences, ranging in topic from epilepsy and medicine to acoustics, music and computing.



**Figure 3.3.1:** Shows the number of EEG sonification papers published each year. As discussed in section 3.4.2 below, the red area indicates papers that used a 'real-time' sonification and the blue indicates 'Off-line' papers.

This survey was carried out by an initial systematic search of Science Direct, PubMed, several scientific databases, Google and Google Scholar, and then a following up of the references in the initial papers. The relatively small number of papers dealing with EEG sonification uncovered in this way suggests a failure of this field to have made a significant or sustained impact on any particular scientific or clinical domain. This view is supported by the observation that the

majority of these papers were conference papers, most of which were 'Proof of Concept' studies.

Many of these authors have championed the potential utility of EEG sonification, but it may be that the failure of most of these studies to rigorously validate their findings that has limited the impact of their work.

### **3.4. Sub-Domains of EEG sonification**

Sonification has been used by a wide range of researchers for a number of different reasons. Therefore as with many multi-disciplinary fields, sonification can be approached from a variety of theoretical perspectives, and at various levels of abstraction. This following section will focus on two dimensions that are critical to this research.

#### **3.4.1. Qualitative vs. Quantitative**

Sonification has shown some utility in the natural sciences, with the Geiger counter perhaps being its most famous example. The Geiger counter clicks at a rate proportional to the strength of radiation it detects and allows the operator to free their eyes from the monitoring of the radiation level and safely navigate environments in real-time. It thereby creates an intuitive continual real-time monitoring interface that is easy to learn and use.

A less well known example is the Voyager 2 space probe mission, whose data visualisation was at one point too noisy to enable the extraction of meaningful information. However, when the probe data was sonified, a hailstorm sound

revealed micrometeoroid impacts as Voyager 2 crossed the rings of Saturn (Kramer et al., 1999).

Some of the earliest and best known examples of EEG sonification have come from the artistic world. For example, in 1965 in "Music for Solo Performer", Alvin Lucier used his own EEG to 'play' musical instruments (Miranda et al., 2008).

But the objectives of the scientific and artistic community are generally quite different. A useful analogy with visualization is given by Thomas Hermann:

"Think of scientific visualization vs. art: what is the difference between a painting and a modern visualization? Both are certainly organized colours on a surface, both may have aesthetic qualities, yet they operate on a completely different level: the painting is viewed for different layers of interpretation than the visualization. The visualization is expected to have a precise connection to the underlying data, else it would be useless for the process of interpreting the data. In viewing the painting, however, the focus is set more on whether the observer is being touched by it or what interpretation the painter wants to inspire than what can be learnt about the underlying data." (Hermann, 2008)

And, as he points out:

"music and sonification are both organized sound, and sonifications can sound like music and vice versa..." (Hermann, 2008)

Therefore, although scientific and artistic applications may record the same data and sonify it in the same way, the methods of analysing or validating the results will need to be very different. A musician may be happy to just listen to the output of the sonification and affirm that it sounds how they intended,

whereas a scientist would need to conduct empirical studies to confirm the sonification's validity and reliability.

Thus, the arts vs. the sciences offer useful examples of qualitative vs. quantitative approaches to validating or assessing sonifications. For example musical EEG sonifications such as Eduardo Miranda's compositions (Miranda et al., 2003) and Mick Grierson's live musical performances (Grierson, 2008) represent qualitative approaches to validation whereas Baier and Hermann's sonification of human epilepsy and John Glen's 'depth of anaesthesia' sonification (Glen, 2010) are examples of quantitative approaches.

The distinction between qualitative vs. quantitative approaches to validating or assessing sonifications will be central for this dissertation, as the question of interest is not solely "how" or even "if" EEG can be sonified but how can it be shown to be useful or how can a sonification be appropriately assessed.

### **3.4.2. Real-Time vs. Off-Line**

In the field of EEG generally, a fundamental and significant division can be made between the use of 'real-time' EEG data for training (i.e., neurofeedback) and monitoring purposes, and the 'off-line' data analysis of the EEG for diagnostic purposes.

Generally for diagnostic purposes the EEG data is analysed off-line, as this gives more time to study the data and allows for a greater range of manipulations, some of which are not possible in 'real-time'. For example the commonly-used signal processing technique of Fast Fourier Transform (FFT) can introduce unacceptable delays (personal communication with Thomas Collura of BrainMaster, a neurofeedback equipment manufacturer, 2010) for 'real-time'



training, because of the windowing method that captures up to 4 seconds of data to compute the spectral power. However, the FFT is a fundamental tool in diagnostic EEG analysis.

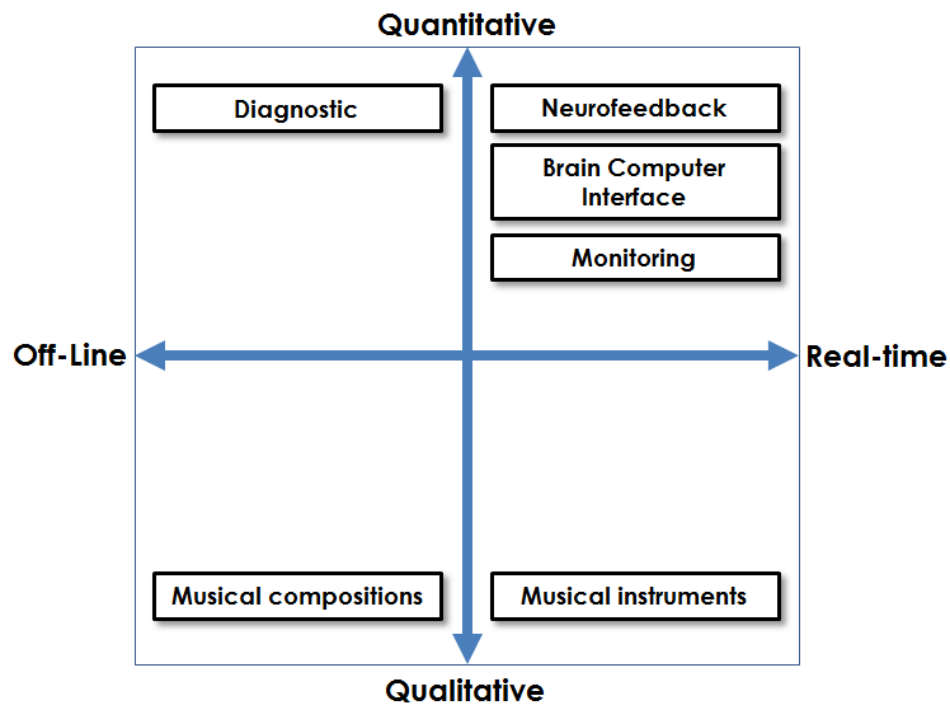
In neurofeedback training, a critical issue is that EEG data must be fed back in 'real-time', minimising any delay in order to facilitate feedback/learning. (Stermann, 2000). This imposes severe constraints on data processing options.

The distinction between real-time and off-line presentation is also important in EEG sonification. For example off-line sonification of EEG data makes possible interactive processes where the data can be a non-continuous, bidirectional, multidimensional sonification of the data to "increase perceptual redundancy" and thereby potentially reduce cognitive workload (Neuhoff, 2011). Such an approach could facilitate perceptual detection and improve data comprehension of the EEG as well as significantly reduce the time taken to analyse long EEG recordings (Olivan et al., 2004). But some sonification techniques, such as time compression (the process of compressing, say, a 30 minute recording into 30 seconds) that may be useful in off-line sonification are not possible in real-time approaches. Obviously there will be many techniques in common between real-time and off-line data processing, but this temporal distinction is crucial for understanding EEG sonification and for this research.

### **3.4.3. Six Application Areas of EEG Sonification**

When reviewing the EEG sonification literature with these Qualitative vs. Quantitative and Real-Time vs. Off-Line distinctions in mind, the two axes can give four quadrants. These are going clockwise, Off-Line-Quantitative (Top Left), Real-Time-Quantitative (Top Right), Real-Time-Qualitative (Bottom Right), Off-

Line-Qualitative (Bottom left). **Figure 3.4.3** reveals six distinct application areas stratified by these two axes and the EEG sonification literature can be mapped into these quadrants.



**Figure 3.4.3:** Shows six application areas of EEG sonification in the 4 quadrants created by a 'Real-Time vs. Off-Line Continuum' on the horizontal axis and 'Qualitative vs. Quantitative Continuum on the vertical axis.

On the qualitative end of the continuum, a temporal distinction can be made between the use of "real-time" EEG sonification for 'live' EEG driven musical instruments such as the pioneering performances of Alvin Lucier in 1965 and 1976 (Lucier, 1976) and more modern examples by groups such as Burak Arslan (Arslan et al., 2006) with their "bio-orchestra". This is where the EEG data of the

performer is captured in 'real-time' and converted into music-like sound. The musician is then able to manipulate their physiology to modify the sound.

At the opposite end of this temporal continuum is much of the work from Eduardo Miranda's Lab that uses EEG data for generative music system to compose music where the output is not necessarily in real-time (Miranda, 2010)

On the quantitative end of the continuum, there is a similar temporal division between the use of 'real-time' and 'off-line' EEG data. At the 'off-line' end is the diagnostic use of EEG sonification. Examples include studies by Hermann and Baier (Baier et al., 2006; Hermann et al., 2004) in which the sonification is used to help detect and localize epileptic activity from pre-recorded EEGs, and work by Olivan (Olivan et al., 2004), which sonifies the polysomnogram (sleep EEG) and can play a 12-hour recording in a few minutes to greatly improve the efficiency of examining the polysomnographic data.

In the area of 'real-time' quantitative EEG sonification, there are three distinct but related sub-domains. The first is Brain Computer Interface (BCI) that uses EEG sonification for feedback and communication for paralysed and 'locked-in syndrome' patients (e. g., (McCreadie et al. 2012). The second is the monitoring of a subject's cognitive state in the emergency room or surgery, such as the 'depth of anaesthesia' monitor from Glen (Glen, 2010). For example, monitoring brain activity allows the anaesthetist to administer a sufficient dose of anaesthetic to stop the patients from waking up or feeling pain, while avoiding increasing the risk of complications and extending the recovery time with excessive medication. Studies have shown a reduction in the amount of anaesthetic used, a reduction in recovery time (Punjasawadwong et al., 2007)

and a reduced risk of mortality using EEG monitoring in surgery (Monk et al., 2005).

The third sub-domain is the use of 'real-time' EEG sonification for EEG neurofeedback to facilitate the learning of self-regulation of cognitive and emotional states, which will be discussed in main part of this chapter in [section 3.7](#) below.

Broadly, the key distinction between real-time monitoring and neurofeedback is who is generating the data and who is receiving it. For example, in a monitoring set-up, a neurologist or anaesthetist will be examining the data produced by a patient and they will use this information to guide their clinical decisions, such as increasing or decreasing the amount of anaesthetic being used. In the feedback set-up, the person hears their own data and they use the information to try to modify their own physiological activity.

Although all 6 sub-domains have much in common, there will be significant, technical, methodological and philosophical differences and the work is likely to be carried out by different disciplines and reported in different conferences and journals. But probably the most significant difference besides the actual sonification techniques used, will be the methods used to validate or assess the sonifications output and impact.

### **3.5. Sonification Techniques**

For all the sub-domains of EEG sonification, the critical issue is how to "map" the data into sound and there are many different techniques. This next section will

categorise and summarise the EEG sonification techniques found in the literature.

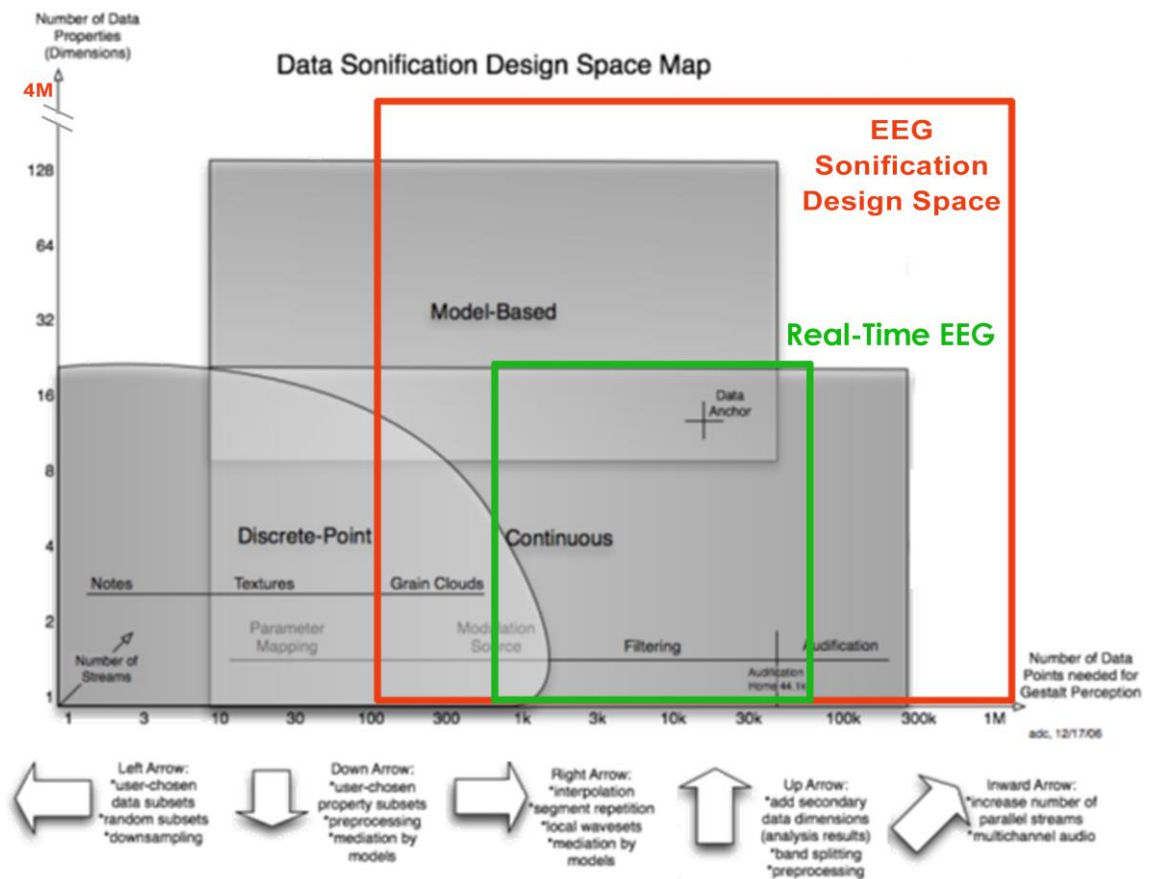
### 3.5.1. Sonification Design Space

Alberto de Campo (De Campo, 2007) proposed a design space map that identified three broad categories of sonification techniques appropriate for different kinds of data: Discrete-Point, Continuous and Model-Based. A dataset's location on this map (See [Figure 3.5.1](#) below) is defined by: the number of data points needed to form a gestalt or whole perception of an event in the dataset; the number of data properties in the dataset; and the estimated number of parallel streams of data that can be meaningfully perceived. de Campo proposes that a sonification design should start with a "data anchor" - a point on the graph that represents the dataset in terms of the number of samples and number of dimensions it has. The possible manipulations of the dataset, such as downsampling, subsetting or interpolation can be represented as movements in the design space map. (as depicted by the arrows at the bottom of [Figure 3.5.1](#))

**Discrete-Point** sonification is more likely to be appropriate for datasets with both a low number of data points and a low number of data dimensions, where individual data events could trigger individual sonic events, and the data dimensions are low enough so that all the events could be heard individually.

**Continuous** sonification techniques would be more appropriate for datasets with a higher number of data points where a continuous representation could form a gestalt of the trends in the data set.

**Model-Based** sonification techniques would be suitable where there are a high number of dimensions in the dataset and the sonification could benefit from reducing the dimensions by downsampling or subsetting.



**Figure 3.5.1:** Data Sonification Design Space Map Adapted from Alberto de Campo (2007). The red and green squares are additions to the original diagram for the purposes of this research, as follows. Based on the number of data points and properties typical of an EEG dataset, the red square has been added to represent the possible design space for the data dimension of a typical “Off-Line” EEG dataset. The green square represents the more restricted data dimension of a “Real-Time” EEG dataset.

The Data Sonification Design Space Map shows the sonification techniques that are appropriate for different data dimensions, Discrete-Point, Continuous and Model-Based. The X-axis shows the number of data points estimated to be needed to form the perception of a gestalt acoustic event. The Y-axis represents the number of properties of interest of each data point, i.e. the number of data dimensions. The overlapping zones are fuzzy areas where different sonification approaches may apply; the arrows refer to movements on the map, which correspond to data manipulations.

### 3.5.2. Defining the area on the Design Space Map for EEG

In order to use de Campo's 'Design Space Map' to better understand appropriate strategies for the sonification of the EEG data, this next section will outline the data dimensions and where EEG should sit in the design space.

In [figure 3.5.1](#), the red and green boxes represent, on the **X-axis**, the number of data points that an EEG dataset can produce and on the **Y-axis**, the number of data dimensions of different EEG applications. The number of simultaneous streams suitable for a meaningful representation of the EEG is represented on the **Z-axis**. This next section will quantify these 3 axes.

**X-axis:** the X-axis represents the number of data points in a dataset. Given that a typical EEG amplifier has a resolution of between 256 to 1024 samples per second and a minimum of 3 minutes of "clean" data is required to get a stable measure of the brain activity. Thus the minimum number of data samples in an EEG record will be somewhere between 46,080 and 184,320 and there could be up to 1.2 million data points for a 20 minute recording.

de Campo suggests "a reasonable first order of magnitude for a good time frame for a single gestalt is the duration of echoic memory, i.e., roughly 1-3 seconds" (Snyder, 2000) therefore this would give around 768 to 3072 data points for a "gestalts epoch". Another way of identifying a suitable time frame of a gestalt is to look at the shape (morphology) of typical EEG activity. So for example a typical EEG alpha spindle has a burst of activity with a duration of between 0.5 to 2 seconds making around 1000 data points.

**Y-axis:** The Y-axis represents the number of data dimensions in a dataset. The raw EEG data has a typical frequency range between 1 and 70 Hz and is generally filtered into sub-frequency bands. The six classic clinical EEG bands are as follows: delta, 2-4 Hz; theta, 4-8 Hz; alpha, 8-12 Hz; beta1, 13-21 Hz; beta2, 21-30 Hz; and gamma, 30 to 70 Hz. Besides these six EEG bands, it is not unusual to subdivide these bands further, for example down to 1 Hz bands. Thus for a single channel (i.e. single measurement location) of EEG, this would give between 1 and 40 dimensions per channel.

When there is more than one channel, then three new comparative dimensions can be derived. These are: amplitude asymmetry (the relative power between left and right homologous sites e.g. F3 in comparison to F4); coherence (a measure of the degree of association between two different parameters) and phase (the delay or "lag" between two channels) Therefore with every additional channel there is a multiplication of these three relationships for each frequency band.

So for example, a 4 channel system with 6 EEG bands, would give 6 Absolute Power variables, 6 Relative Power variables and 15 Power Ratio variables



(Power Ratios are a measure of the relationships between different frequency bands in the same location. For example: the theta/beta ratio is computed by dividing the theta power by the beta power). This makes a total of 27 variables for each channel (these can be seen as 'Within Channel variables')

Since the 4 channels have 6 connections (or links) between each channel and each would have a Coherence value for each of the 6 EEG bands, plus 6 for Phase Difference, making a total of 12 variables for each connection (Between Channels). Therefore a system with just 4 channels would have 216 data dimensions.

Whereas a typical 19 channel EEG system with 6 EEG bands would give 171 links and 3591 data dimensions a 19 channels system with 30 EEG bands would give 15,903 data dimensions and a 256 channels system with 40 EEG bands gives 3,923,712 data dimensions.

This suggests that according to de Campo's, 'Data Sonification Design Space Map' that EEG sonification lies mostly in the 'Continuous' data representation space but overlaps the border with 'Model-Based' and 'Discrete Point' data representation.

The **Z-axis** in [Figure 3.5.1](#) represents the number of simultaneous streams suitable for a meaningful data representation. In a visual display for neurofeedback for example, it might be usual to have 3 or more concurrent streams of EEG band power, for example theta, alpha and beta displayed at the same time, and to ask the trainee to focus on, for example, increasing the power of the alpha whilst simultaneously lowering the theta and beta. The sonification of EEG offers the potential to present multiple parallel streams of EEG data and this could

assist in creating a meaningful gestalt out of the complex EEG data. It is an empirical question to see how many simultaneous streams of EEG sonifications people would be able to comprehend and clearly this would be dependent on the type of sonification.

### **3.5.3. EEG Sonification Techniques**

Over the last 83 year history of EEG sonification, one of the principal motivations cited by authors for proposing the use of sonification to “display” EEG has been to reveal the temporal complexity of the EEG signal. Authors argue that this temporal complexity is lost in visualization techniques and suggest that the human auditory system is particularly well suited to the perception of EEG.

This section will focus on the subcategory of sonification techniques that are capable of the real-time presentation of the EEG. (More information on these techniques is given in [Appendix: A2.4 Sonification Techniques](#)).

The 21 real-time EEG sonification techniques found in the literature survey have been categorised for the purposes of this review using de Campo's sonification design space map into three broad groups (Discrete-Point, Continuous and Model-Based).

As can be seen in [table 3.5.3](#) below; straightforward audification is the earliest, and one of the most popular, sonification techniques, with six examples occurring in the literature survey; this popularity may be as much to do with its simplicity to implement as its utility.

Only six of the sonification techniques have been used in a neurofeedback study. With the most popular being Amplitude Modulation with five

neurofeedback studies and both Frequency Modulation and threshold sonification technique with three neurofeedback studies each.

Of the 14 EEG sonification neurofeedback studies only 12 will be reviewed in this chapter as the Le Groux, 2009 and Trevisan, 2011 studies did not attempt to validate their work or provide sufficient detail to allow analysis.

Although de Campo's sonification design space map helps, from reviewing the EEG sonification literature it would be very difficult to draw a conclusion as to which technique is most appropriate for a particular application. There is no standardised framework for reporting or categorising the different sonification techniques and very little quantitative evaluation of different techniques. Without this necessary foundation it can be difficult to know which sonification techniques to use for a new EEG sonification task.

		Sonification:	Study name:
Parameter-Mapping Sonification	Continuous	Audification	Adrian 1934, Jovanov 1998, Olivana 2004, Baier 2005, Wu 2009, Khamis 2012,
		Amplitude Modulation (7/5)	Hardt 1978, Baier 2005, Hinterberger 2011/16, Choi 2011, Hardt 2012, Wang 2013
		Frequency Modulation (7/3)	<b>Fell 2002</b> , Hinterberger 2004, Wu 2009, Miranda 2010, <b>Trevisan 2011</b> , <b>Hinterberger 2011/16</b> , Lu 2012
		Filtered Sonifications (1/1)	van Boxtel, 2012
		Spectral mapping	Hermann 2002
		Distance matrix	Hermann 2002
		Differential	Hermann 2002
		Neurogranular sample	Grant 2000
		Timbre mapping	Baier 2005
		Parameter mapping (2/1)	Hermann 2006, <b>Ramirez 2015</b>
	Discrete Point	Event-based/Threshold (10/3)	<b>Nowlis 1970</b> , <b>Schwartz 1976</b> , Jovanov 1998 <b>Allen 2001</b> , Arslan 2006, Baier 2006, Brouse 2006, Baier 2007, Franco 2015, Chen 2015,
		Auditory icons	Salter 2008
		Earcons	Jovanov 1999
		Flanging (2)	Arslan 2005a, Arslan 2005b
		Granulation (3)	Arslan 2005a, Arslan 2005b, Filatriau 2006
		Extrema detection	Hinterberger 2004
Model-Based		Generative rules music	Brooks 2007
		Kernel regression	Hermann 2008
		Tristimulus synthesizer (1/1)	Le Groux 2009
		Overtone mapping	Terasawa 2012
		Spatial location	Baier 2007

**Table 3.5.3:** Shows the 21 sonification techniques that have been used to display real-time EEG. The bold blue text highlights the 14 neurofeedback studies and the numbers in the brackets show total number and neurofeedback studies. The sonification techniques categorised according to de Campo's sonification design space map into three sub-groups; Discrete-Point, Continuous and Model-Based. See [section 3.5.1](#) de Campo's definitions and appendix "A2.4 sonification techniques" for a description of the different techniques.

### **3.6. Assessment of EEG Sonification**

By definition, the primary objective of sonification is to aid in the perceptual detection of salient features in the data. Thus, as will be argued below, it is somewhat surprising that so few EEG sonification papers have offered any quantitative or listening assessment of their sonification output. It is clearly important to test the ability of a sonification to convey the “signal” in the data in a manner that the human listener can perceive. Indeed, this would appear to be a prerequisite for any scientific work on sonification. This seems particularly important with EEG, given the very high temporal resolution and noisy nature of the EEG signal, by comparison with some other targets for sonification, such as seismological or stock market data. But a failure to validate sonifications applies more widely than to the field of EEG alone. In a systematic review of mapping strategies for the sonification of physical quantities, Dubus (Dubus and Bresin, 2013) makes the same complaint and can find only one example where two sonification techniques have been compared side-by-side.

Presented below is a summary of 5 papers that did conduct a perceptual listening test of the sonification output.

#### **3.6.1. Aesthetic Assessment**

Wu, Li and Yao (2013) sonified Alpha EEG from participants with their eyes closed and eyes open and attempted to make the output of the sonification more ‘musical’ by using artistic beats and tonal filters.

Subsequently, 22 participants were played 4 different 60-second sonifications of single- or multi-channel EEG from two conditions: eyes closed and eyes open. Participants were asked to rate each sonifications on a 9-point scale, on 6-

criteria; tempo, valence, arousal, rhythm, musicality and richness, (These terms were not defined by the authors in this paper). The authors concluded that:

"... the notes in eyes closed music were longer in duration, lower in pitch and slower in tempo, which demonstrated a peaceful and quiet mood corresponding to the eyes closed state. In contrast, the notes of eyes open were shorter in duration, higher in pitch and faster in tempo, which meant that the brain was relatively alert and active."

But, not pointed out by the authors was that this musical correspondence is a product of the sonification mapping, not any intrinsic musical properties of the signals corresponding to eyes closed and eyes open brain activity, thus rendering the assessment of the sonification aesthetic qualities somewhat superfluous.

### **3.6.2. Two-alternative Forced-Choice Method (2AFC)**

In a paper by Loui (Loui et al., 2014), fifty-two naive participants were given a 'two alternative forced-choice test', where they were asked to listen to several 10 second sound files of sonified EEG and for each one, to choose if the file contained epileptic seizure activity or not.

The experiment consisted of three separate blocks in one session. In the first block, without any training, participants listened to 26 sound files, half of which contained epileptic seizure activity and the participants had to choose if the file had seizure activity or not. In the second "Training" block, 3 sound files with and 3 without seizure activity were played and the participants were informed which category the files belong to. The third block was the same as the first but

after training. Loui showed that with a very short training protocol, participants were able to identify seizure activity at a better than chance level.

Vialatte et al. (Vialatte et al., 2009, 2012) took the EEG data from elderly patients suffering from mild cognitive impairment (MCI) who would go on to develop Alzheimer's disease within a year and a half and compared them to healthy age-matched controls. The 5-minute eyes-closed EEG data was reduced in complexity by a sparsification process called bump modelling that tries to highlight only the prominent features in the data set.

In a perception test after 30 minutes of training, Five listeners were played the sonifications of 5 MCI patients and 5 control subjects and asked to rate them as either "certainly MCI", "unsure" or "certainly healthy". Four out of five listeners classified all patients correctly, giving an overall error of 11%.

### **3.6.3. Temporal Onset Detection**

Khamis, Mohamed, Simpson, and McEwan (2012) sonified 2 channels of 24-hour EEG recordings from 17 patients with temporal lobe epilepsy by speeding the data up by 60 times to move it into the audible hearing range. This is called audification and is one of the simplest methods of converting time series data into sound. Khamis and colleagues then played the sound files to five listeners to see if they could detect the onset of the epileptic seizure activity and localise which hemisphere the seizure begins. After a 2-hour training session, the participants were played different examples of sonified EEG alpha, theta and delta waves, as well as movement artifacts and epileptic activity from 7 of the epilepsy patients. They then spent a mean of 17.2 hours listening to the remaining 10 epilepsy patients' EEG data. The listeners were able to detect the

seizure with a mean sensitivity (i.e., true positive rate) of 81.3% and a false positive rate of 0.012 per hour. The average lateralisation accuracy of epileptic seizure for all five listeners was 77.62%, with a standard deviation of 7.14%.

Khamis et al. went on to claim that:

“With a limited amount of training human listeners can identify seizures and seizure lateralisation from audified EEG signals from electrodes placed at P3-T5 and P4-T6 (left and right parietal and temporal lobes) with a sensitivity comparable to electroencephalographers /epileptologists detecting visually from EEG traces with 21 electrodes... with greater than a factor of ten improvements in the rate of false detections per hour”.

This is an interesting study in that it shows that inexperienced “listeners” can detect features in the EEG data from the simplest form of sonification, i.e., audification. Furthermore, these inexperienced “listeners” were able to achieve detection accuracies equivalent to trained EEG experts.

Alexis Kirke and Eduardo Miranda (Kirke and Miranda, 2012), attempted to sonify the emotional arousal and valence of Kirke while he was listening to ambient music, hard rock and silence. Arousal and valence can be inferred by the relative activity of the left and right frontal cortex with a metric called “frontal alpha asymmetry” (Davidson, 1998) see [section 2.1.11](#) in chapter 2.

Three “listeners” were played two sonifications with five affective changes in each file. The task was to identify any perceived changes in valence and arousal of the sounds of the EEG data. Kirke and Miranda suggested: “there is an average of 80% communication rate for Valence and 70% communication



rate for Arousal." Unfortunately they appeared to only count correct hits and not false positives and did not give much detail on the listening test.

#### **3.6.4. Key issues in the assessment of EEG sonification**

In summary, to date some EEG sonification studies have used the 'two-alternative forced-choice method' (2AFC) to assess a sonification's ability to convey information, e.g., distinguishing between patient with epilepsy versus a non-patient (Loui et al., 2014), or patients suffering from mild cognitive impairment versus healthy age-matched controls (Vialatte et al., 2009, 2012). Some of these studies have shown very good detection accuracy but this method does not really capture the temporal aspects of perception of the sonified data, an aspect of EEG sonification that we will consider below.

Some studies captured some of the temporal information by asking participants to identify the time of onset of a particular EEG activity. So, for example, Khamis (2012) played two channels of EEG sonification of patients with temporal lobe epilepsy and asked the study participants to push a button when they heard the onset of seizure activity. After only 2 hours of training, non-expert listeners could perform this complex detection task to an expert level. However, epileptic activity has significantly larger amplitude and a very different morphology compared to background EEG, and thus is easily distinguished. Although this is an important area for applying EEG sonification, it is also somewhat specialized, since epilepsy only affects around 1% of the population (Thurman et al., 2011).

From the point of view of assessing the temporal resolution of a sonification this kind of assessment has the potential to offer more information than the 2AFC

method, but it does little to assess the full range of dynamic characteristics of listening to continuous sound-based feedback.

Physiological data tends to be complex and noisy, consequently a person's response and their attempts to comprehend that data may be similarly complex. Unfortunately none of these assessment methods seems to capture the complexities or temporal dynamics of the listening task.

Thus the development of a methodology that could assess the ability of sonifications to convey temporally rich EEG data in real-time could greatly assist the design and selection of appropriate sonifications for a range of application areas such as neurofeedback, surgical monitoring, or brain computer interfaces (BCIs).

### **3.7. EEG Neurofeedback Sonification literature**

Up until this point this chapter has given a brief review of the history and research field of EEG Sonification, as well as identifying six application Sub-Domains. Then this chapter looked at the sonification techniques that have been used with EEG and reviewed the assessment methods that have been used to date.

This next section will give a summary of the papers found that have used EEG sonification specifically for neurofeedback. At the end of the section are two tables that summarise critical aspects of the 12 studies considered.

Joe Kamiya presented a paper at the meeting of the Western Psychological Association in San Francisco in April 1962, called "Conditional discrimination of

the EEG alpha rhythm in humans" (Kamiya, 1962) and E. Dewan presented a paper in June 1969 at the Symposium on Biomedical Engineering, at Marquette University, called "Communication by voluntary control of the electroencephalogram (Dewan, 1969). Unfortunately, both conference papers have proven difficult to find.

### **3.7.1. Nowlis, 1970**

Therefore, David Nowlis and Joe Kamiya's paper (Nowlis and Kamiya, 1970) in Psychophysiology in 1970 appears to be the earliest available example of EEG neurofeedback sonification, published decades before the word sonification was even coined. In this 'Non-blinded', 'Within Subject' study design, Nowlis and Kamiya gave an "auditory feedback loop keyed to the presence of alpha". Twenty-six subjects were played a 520 Hz tone whenever their alpha activity (8 to 13 Hz) was greater than 20 microvolts.

Within 1 session:

"The subject was given approximately 2 minutes to get used to the tone coming on and off. He was then given a two minute baseline trial, with his eyes closed and the instruction to remain still, and with the tone appearing with alpha. After this baseline test, subjects were instructed to try to figure out what made the tone come on and what made it go off. They were told to inform the experimenter when they felt that they had some insight into the problem, and he would then proceed to give them another two-minute trial during which they should try to keep the tone on as much as possible. The experimenter then allowed the subject up to 15 minutes to experiment with the tone. The experimenter never directly suggested the use of any tactics, besides warning

against vigorous movement of the eyes or body... a second trial was run for keeping the tone off".

Two EEG channels were recorded from occipital-frontal and occipital-central, with the ground on the right ear. The channel with the largest amplitude of alpha was used, and this was the central-occipital channel in 15 of the 26 cases. Ten subjects with a high eyes closed alpha, train with eyes open and the other Sixteen worked with eyes closed.

"All subjects were given an open-ended post-session interview. They were asked to describe their methods of turning the tone off and on".

Nowlis and Kamiya reported:

"The degree of control over alpha can be quantified by comparing the number of seconds out of 120 that the tone indicative of alpha was sounding under the three conditions of (a) a relaxed baseline, (b) the last trial on which the attempt was being made to keep alpha on, and (c) the last trial on which the attempt was being made to keep alpha off.

Every subject (26 of 26) succeeded in having more alpha during the final "on" trial than during the final "off" trial.

For 21 of the 26 subjects, the amount of alpha in the "on" condition was increased over that in the relaxed baseline period; for 19 of the 26 subjects, the amount in the "off" condition was decreased below the baseline condition. Using the sign test, the tendency toward change in the "on" trial relative to baseline is significant at the .01 level and in the "off" trial relative to baseline at the .05 level".

This is a very impressive result for one session, despite some methodological issues. It should be remembered that both EEG and audio equipment were quite crude and cumbersome in the 60s and 70s in comparison to today. For example, real-time EEG visualisation was on a paper trace.

Probably partly because of these equipment constraints, subjects received slightly different protocols: the high alpha groups trained with eyes open and low alpha groups with eyes closed, and the scalp locations with the highest alpha amplitude were used in order to ensure sufficient alpha amplitude to measure.

Most problematic in terms of study design, was the fact that the feedback tone was played to all the subjects only when the alpha activity was greater than 20 microvolts. As there is such large variation, both between and within subjects in EEG and in alpha particularly, this would mean that some of the subjects would receive either too much or not enough feedback in order to learn how to control their alpha activity and this could have inhibited their learning. Looking at the results this would seem to be the case, as the percentage of time each subject received feedback ranged from 5% to 92% at baseline. Tellingly, the subject with the 5% baseline could raise the “on” trial alpha to 58% but could not lower the “off” trial alpha below baseline, with a score of 12%. However, the subject with the 92% alpha over threshold at baseline could lower the “off” trial below baseline to 51% but could not increase the “on” trial with a score of 86%.

As noted by Nowlis and Kamiya, “Because of this there was considerable variation in the percentage of time that various subjects tended to hear the tone during their trials.” By group, the eyes-closed subjects with the lower

baseline alpha on average received the tone only 29% of the time at baseline and 22% in the "off" trials and 44% in the "on" trials. In comparison, the eyes-open subjects had on average feedback 48% of the time at baseline, and 13% in the "off" trials and 64% in the "on" trials.

With modern EEG equipment that can record a greater dynamic range to a higher resolution it would not be necessary to select electrode location and eyes-closed or open conditions in order to keep the alpha amplitude in an optimal range for the equipment. So it would be easy to run a more consistent protocol, within which all the subjects trained with either eyes closed, or eyes open, and the EEG was taken from the same scalp location, while still allowing each subject to receive an optimal level of feedback with individualised reward thresholds. This could help to separate out whether it is just the subjects with high alpha that show the ability to control their alpha levels, or if it is something to do with the eyes being closed or open or with scalp location or most likely the amount of feedback given. We now know from newer research (Kropotov, 2010) there are several types of alpha rhythms at different scalp locations, reflecting different neuronal networks and processes, so the choice of location could be critical.

Interestingly, Nowlis and Kamiya reported that: "Dewan was able to learn to control the presence or absence in his own EEG record so well that he could use his EEG to send messages to a computer in Morse code." (Unfortunately, the Dewan paper does not appear to be available today).

Hardt and Kamiya (1976), in a later paper called "Conflicting Results in EEG alpha Feedback Studies", did highlight the shortcomings of the fixed-threshold

protocol design used in their 1970 study, as this design does not permit full representation of the amount of alpha activity of the individual, and there are occasions where the subject can increase the amount of alpha without receiving any more reward. For example, it does not matter how much the EEG activity is over the threshold because the sound only represents 'when' the EEG activity is over the threshold.

### **3.7.2. Schwartz, 1976**

Gary Schwartz, Richard Davidson and Eric Pugash (Schwartz et al., 1976), reported on a simple tone sonification neurofeedback where people received a reward tone when their alpha (8-13 Hz) activity in parietal (P3 and P4) met criterion in three different types of trials (see below).

In this 'Single-blinded', 'Within Subject' study design, 20 right handed subjects (10 females) with eyes closed, received 3 times 1 min of EEG symmetry training in each of three trials (i.e. 9 mins). In the first trial participants received a reward tone when their left alpha power was low and right alpha power was low (Low-Low) i.e. lowering the alpha on both sides. In the second trial they would get a reward tone when their left alpha was low but their right alpha was high (Low-High) and the third trial was the opposite i.e. left alpha high plus right alpha low (High-Low).

After each trial participants completed a questionnaire to assess their cognitive strategy during the trial, "to what extent would you say your strategy for turning on or off the tone, involved the following kinds of thoughts?" There were 6 Categories: a) verbal, b) numerical, c) visual, d) musical, e) emotional, f)

thinking nothing and they had to circle a number from 1 (not at all) to 7 (nearly exclusively).

Schwartz et al. concluded that:

"These data indicate that when uninstructed subjects are given feedback for asymmetrical patterns of EEG alpha activity, they can rapidly acquire significant control over these patterns with relatively brief training (a total of 12 min). The corresponding findings on self-reported cognitions during differentiation training are striking, considering the brevity of the training and the fact that the subjects were completely uninformed with respect to knowledge of which EEG parameters were being trained".

This study was not specifically concerned with the neurofeedback training, but was interested to establish the cognitive concomitants of the different parietal asymmetry patterns in each trial condition.

Again it should be noted that the equipment used was an pen and paper polygraph system, where individual alpha activity was calibrated to yield a 3 cm pen deflection and criterion value was set to trigger in response to a signal at or exceeding 1 cm, so that alpha activity had to be at least 33.3 % of the average peak amplitude. This was a well-designed study as the participants were blind to the different conditions and it did address the issue of individual reward thresholds.



### 3.7.3. Hardt, 1978

Following on from their findings in the 1976 paper, Hardt and Kamiya reported a second alpha sonification study in *Science* (1978), but this time the loudness of sonification feedback was proportional to the instantaneous alpha voltage (i.e. amplitude modulation). This means the feedback was continually varying across the full range of alpha activity, not just when the alpha amplitude was over a pre-set threshold. In this 'Non-blinded', 'Within Subject' study design, the 8 highest and 8 lowest trait-anxiety subjects, as measured by the Minnesota Multiphasic Personality Inventory (MMPI), were picked from 100 male college students and trained for 7 sessions:

"Each day we recorded from each subject (i) mood scales, (ii) an 8-minute resting baseline, (iii) 32 minutes of alpha enhancement feedback, (iv) mood scales, (v) an 8-minute resting baseline, (vi) 16 minutes of alpha suppression feedback, and (vii) mood scales. Subjects sat erect, eyes closed, in total darkness for all recording. Mood scales included the "state" form of the Multiple Affect Adjective Check List (MAACL) to measure changes in state anxiety during feedback".

They found that: "Alpha enhancement reliably reduced state anxiety in the high trait-anxiety group." And: "The inverse relation was "complete" in that alpha suppression increased state anxiety".

However, "low trait-anxiety subjects showed no significant alpha/state-anxiety effects." They concluded: "Reductions in trait anxiety were large enough to be useful in anxiety therapy." It should be noted that the subjects were taken from

a student population, so even the highest trait-anxiety students are not likely to have a clinical diagnosis of anxiety.

This study represented a significant methodological improvement on the Nowlis and Kamiya study in two main ways. First, they recorded pre- and post-training behavioural measures and showed that they correlated with the changes in the physiological training measures. Second, the feedback of the alpha activity was of the full range of alpha amplitude, meaning that all subjects would have received feedback regardless of their baseline alpha level.

Although the sonification in which the amplitude of the sound is proportional to the alpha amplitude seems reasonably intuitive, there have been some criticisms of this technique in the sonification world (Glen, 2010). It is suggested that human auditory perception is more sensitive to frequency modulation than amplitude modulation, and that users would need to set the sound amplitude to a comfortable level, thereby losing any absolute reference value to the alpha activity between sessions.

#### **3.7.4. Allen, 2001**

In a rigorous and controlled, 'Single-blinded', 'Between Subject' study design, John J.B. Allen, Eddie Harmon-Jones And James H. Cavender (2001), explored the asymmetrical activation of the anterior cortex, by manipulating the frontal alpha asymmetry of participants using auditory neurofeedback, then assessing their responses to three different emotionally evocative film clips that elicit happy, neutral, or sad emotional responses.

18 right handed female participants were randomly assigned and blind to one of two groups. One group received reward when their alpha (8-13Hz) activity

on the left frontal cortex (F3) was greater than the alpha on the right (F4) and the second group was vice versa. The participants were not suffering from depression.

In five sessions consisting of 5 blocks of 6 min with 1 min breaks between, participants would hear either a 300 Hz tone when they were above criterion or a 150 Hz tone when below (i.e. when left alpha was higher than right or vice versa).

Because the researchers were concerned that the amount of reward a participant receives during a training session could affect their emotional response, in order to keep the amount of reward the same throughout the sessions and between subjects, a slightly unusual thresholding procedure was used.

For each block of 150 2-s epochs for the first second of each 2-s epoch the mean and standard deviations of the R-L alpha activity was computed and if it was greater than 0.85 standard deviations over the mean for the 'LEFT' participants and less than - 0.85 SD for the 'RIGHT' participants then the reward tones were presented.

Allen suggested that "This criterion value should, assuming a normal distribution of right-left values across the 150 epochs, result in reinforcement on approximately 20% of the trials"

The authors concluded: "Systematic alterations of frontal EEG asymmetry were observed as a function of biofeedback training. Moreover, subsequent self-reported affect and facial muscle activity (EMG) in response to emotionally evocative film clips were influenced by the direction of biofeedback training."

and that "The present study must be regarded as preliminary..., but supports the hypothesis that manipulation of frontal EEG asymmetry, and by inference cortical activity, alters the pattern of emotional responding consistent with predictions derived from theoretical accounts of frontal brain asymmetry"

This study was not specifically focused on neurofeedback per se, or the nature of the sound feedback, but on using it as a tool to manipulate frontal alpha asymmetry. They showed that as a group the participants were able to modify their frontal alpha asymmetry and this was reflected in their emotional responses to emotionally evocative film clips.

Perhaps the biggest criticism of this study and maybe why only half of the participants were classified as responders, could be due to the use of criterion feedback with a very low percentage of reward. It was designed to be around 20%, but the reward percentage was in fact only 13.75%. It is commonly suggested in the neurofeedback community that, based on operant conditioning learning theory, the optimal percentage of feedback should be around 70%. If the feedback is higher, then participants find it too easy and do not acquire the skill, whereas if it is lower, then it is too difficult and they have trouble maintaining motivation (Othmer & Othmer, EEG spectrum training course, 1999). Such a low percentage of reward could be part of the explanation for why despite showing increases in the training parameters over the first four days, the last session did not show any training effects.

### **3.7.5. Fell, Elfadil, 2002**

In this 'Non-blinded', 'Within Subject' study design, in one session Jürgen Fell, Hakim Elfadil And Peter Klaver, (Fell et al., 2002) trained 13 subjects to increase their alpha power by decreasing the frequency of a 250 Hz tone. "An increase of alpha power during the training trial above average baseline level was transformed into a frequency decrease of the feedback tone". The sessions consisted of 3 lots of 3 trials of 2-and-a-half minutes (i.e. 22.5 minutes overall) interspersed by 4 baseline trials of 1 minute. Fell was more interested in the relationships between the different EEG parameters than in the learning outcomes of the alpha training, and he found "a highly significant correlation between alpha power and spectral entropy within the alpha range during biofeedback training".

### **3.7.6. Le Groux, 2009 and Trevisan, 2011**

Reported for the sake of completeness: Le Groux (Le-Groux and Verschure, 2009) and Trevisan (Trevisan and Jones, 2011) both published papers on EEG neurofeedback sonification, but neither attempted to validate their work, so no further comment is warranted.

### **3.7.7. Hinterberger, 2011 & 2016**

In a 'Non-blinded', 'Between Subject' Pilot Study, Thilo Hinterberger (Hinterberger, 2011) combined sonification and light-driven EEG to train a range of 6 EEG frequencies and heart rate in 20 subjects, half of whom were experienced meditators and the other half novices. The subjects sat for 15 minutes in a room illuminated with coloured light, where the brightness would fluctuate with the amplitude of the ultraslow potential (0.01 to 0.2 Hz) and the

alpha brain waves. A complex protocol of sonification that varied over the course of the sessions was played simultaneously. The physiological data could modify four different Midi note parameters (touch, velocity, pitch, and amplitude) for a range of instruments.

The participants were instructed: "Before exposed to the stimulation the users should be informed about the fact that every instrument or sound they hear and every change in light or colour will be initiated by their own body signals." After the session, subjects filled in a mood questionnaire, and "The participants were given the opportunity to describe in their own words their personal impressions and feelings they had during and after the session." 15/20 people experienced an increase of their bodily awareness, as well as a number of other effects.

As a follow-up/replication to this study, Hinterberger & FÜRnrohr (2016), conducted a 'Non-blinded', 'Within Subject' study design, consisting of six intervention trials, of which, three were control and three experimental groups. An active control group 1, was a Mindfulness Meditation exercise, a second, active control group 2, was a "Body Scan" exercise, intended to increase the participant's perception of their body and the third control group called, Pseudo-Sensorium was a NON intervention passive or "sham" feedback group, where pre-recorded data from a different person was played back through the feedback system.

The first experimental group was called Sensorium-1, and focussed on the feedback of heart rate variability and was intended to replicate the effects of the Mindfulness Meditation control group. The second group called Sensorium-

2, used the EEG and ECG to replicate the Body Scan control group. The third Sensorium-3 group was also a real feedback of EEG and ECG but a slight modification of the second and it was compared to the Pseudo-Sensorium and participants were instructed to "just enjoy the experience as an audio-visual relaxation exercise."

36 participants "of whom 72 % practiced meditation", did all six interventions which lasted around 20 min each.

Hinterberger concluded that the results suggest "that a real and honest feedback of the signals is essential for the successful implementation of the Sensorium approach." And "feedback questionnaire assessed the participants' subjective reports of changes in well-being, perception, and life-spirit. The results indicate that the Sensorium sessions were not statistically inferior compared to their corresponding active control conditions..."

This within subject study design with a complicated light and sonification feedback protocol of multiple channels and parameters of physiological activity, attempted to induce a meditation state. Much was made of the statistical difference between the experimental groups and the passive Pseudo-Sensorium control group. But probably the biggest problem with this study was in the sham passive Pseudo-Sensorium control group. The authors say, "For conformity reasons the participants were instructed that they now were not perceiving their own signals and therefore should just enjoy the experience as an audio-visual relaxation exercise."

The fact that the participants were not blind to group does somewhat undermine the majority of the claims made in this paper

### 3.7.8. Choi, 2011

In a 'Non-blinded', 'Between Subject' placebo control study with 23 depressive disorder patients, Sung Won Choi, Sang Eun Chi, Sun Yong Chung, Jong Woo Kim, Chang Yil Ahn and Hyun Taek Kim (2011) trained frontal alpha asymmetry in half the patients with a simple sound based feedback where the volume of a piece of classical music (Franz von Suppé 'Light Cavalry Overture') would vary with the amount of asymmetry when the right alpha was greater than the left. The EEG was recorded from right frontal (F4 = R) and left frontal (F3 = L), both referenced to the vertex (Cz, top of head). The asymmetry was calculated as:  $Asy = (R - L)/(R + L)$ . "The participants were told to try to keep the sound on and to try to continuously raise its volume." They trained for two sessions a week for 5 weeks and each session consisted of 6 four minute trials followed by 5 thirty-second rest periods.

A comprehensive pre and post-test battery of psychometric and interview data was collected as well as daily stress and depression inventories. The control group received basic psychotherapy training but patients and evaluators were not blinded to group. The neurofeedback training showed a specific increase in absolute alpha power at F4, and improved asymmetry scores, which was suggested to indicate an "induced left frontal dominance". Supporting this finding, Choi found "50% of the subjects showed clinically meaningful changes, which were not found in the psychotherapy placebo group"

In a 1-month follow-up of the neurofeedback group the authors conclude "Subsequent analysis showed that differences in all physiological, clinical, and neuropsychological assessment scores between the post-training and 1-month



follow-up were not significant." This suggests the training changes have lasted for a month; however they do not appear to present the follow-up EEG data.

This research studied a patient population and a control group, although they were not blind to group membership. There were only 12 people in the intervention group but they did get a statistically and clinically significant reduction in depressive symptoms and "No participants reported significant side effects". The EEG was only recorded from the two scalp locations, F3 and F4, but the expected changes in alpha asymmetry and no changes in the other EEG bands did coincide with the psychometric changes.

A plethora of psychometric measures were collected but for many no theoretical reason was given to explain the relevance for depression or alpha asymmetry. Moreover a series of group by time ANOVAs were run on the individual measures but no alpha asymmetry by psychometric interaction appears to have been presented. This is a shame as this would probably be the most interesting outcome metric from successful as well as unsuccessful patients. After all it could be possible that, half the respondents changed their alpha asymmetry and the other half improved their depressive measures but it is not possible to tell from these results.

Of course it would be nice to have bigger group sizes with a double blind sham control group and full cap EEG pre and post. But with already, probably around two months of data collection, this is an encouraging result from a two-channel alpha neurofeedback training with such a simple and user friendly sonification.

### 3.7.9. van Boxtel, 2012

Probably, the most rigorous and methodologically-sound EEG neurofeedback sonification study was reported by Geert J.M. van Boxtel, (van Boxtel et al., 2012). In this randomised, double-blind, 'Between Subject' placebo-controlled study, 50 healthy participants received 15 sessions of one of three interventions. One group received auditory alpha activity training (N=18), a second group received random beta training (N=12), and the third did not receive any training at all (N=20).

The subjects were able to listen to music of their own choice, and in the two training groups the EEG band power recorded from the sensorimotor strip in the centre of the head would affect the sound quality of the music. Thus, in the alpha group as the alpha power decreased, the quality of the music would decrease proportionately in real-time. In the active control group a different Beta band would be selected randomly every session in order to inhibit any learning effects. In the passive control group subjects would have their EEG recorded while listening to their music, but there would be no change in the sound quality.

In a comprehensive test battery of pre- and post-measures of 26 channel EEG and Event-related potentials, as well as mood rating scales, quality of life inventories, sleep rating and guided interviews, van Boxtel et al., were able to show that only the real alpha training group could increase their EEG alpha activity by 10%, and that the increase "remained evident 3 months after the last training session". In an exit interview, the alpha training group did feel more relaxed, but despite showing trends in the right direction no statistically significant behavioural measures of stress and relaxation were reported. The

authors suggested that this was due to the lack of statistical power because the group sizes were too small.

Although this was an excellently designed and controlled study, there are three main issues that could explain the failure to show a behavioural change with the EEG training. First, the authors suggest that modern life is stressful and point out that 40 million workers in Europe suffer from the negative effects of stress. (Europe has a population of around 740 million people, so 40 million would be around 5.4% suffering from stress). The 50 subjects were recruited from a website, and there was no suggestion they came from a stressed population. This would mean that on average there could be 3 subjects suffering from stress-related conditions, and the majority of subjects would not be particularly stressed or likely to receive significant benefit behaviourally from general alpha enhancement training.

The second issue is that the subjects were allowed to listen to their own choice of music, without control for the genre and style of the music. Given that the participants were not informed of the purpose of the study, it is quite possible that they were listening to arousing music. This is supported by the fact that, despite numerous studies showing the relaxing effect of listening to relaxing music, in this study even the music-only group failed to show significant increases in relaxation.

Of course it could be claimed that the behavioural measures used in this study were capturing trait properties of the subjects that should not be expected to change over a short period of time. Or that the measures were just not sensitive enough to any change that may have happened.

But perhaps the most significant difference between this study and the others mentioned above is that the subjects were not given any instructions or even told their EEG could control the sound quality; they were only asked to “sit back and relax”. The authors suggested that, as the participants were listening to music that they knew well, and the reduction in sound quality was very obvious, the task was a “very intuitive feedback mechanism”. This could be correct, as with this very simple sonification method the training group did make lasting changes in their alpha levels that remained for 3 months. But the lack of explicit instruction may account for the lack of behavioural change.

One explanation for this may be that, despite the human auditory system's incredible ability to continually trace or alert to sound, it also has the ability to block unwanted or irrelevant sounds. Maybe precisely because the subjects were familiar with the music they were listening to, they were able to ignore the distortion.

This highlights an interesting and potentially critical distinction in the neurofeedback domain, that between explicit and implicit instruction. In most clinical neurofeedback training, a great deal of explanation is given to the subjects about the procedure, and they are encouraged to focus explicitly on trying to manipulate the EEG activity and how they feel as they change the EEG parameter. But in studies that use implicit neurofeedback, it is not so clear what the learning mechanisms would be.

### 3.7.10. Hardt, 2012

37 years after his first paper on alpha neurofeedback, a pioneer in the field James V. Hardt, (2012) reported on a study of 40 adults undergoing an intense alpha neurofeedback training procedure, which consisted of daily sessions of between 76 and 120 minutes for 7 consecutive days.

The alpha amplitude of four channels (O1, O2, C3 and C4) controlled the amplitude of four tones (400-800 Hz) (i.e. AM) played on four different speakers in four different spatial locations.

The training protocol consisted of both alpha enhancement and alpha suppression. "For epochs of 2 minutes at a time, the trainees sat in the dark with their eyes closed listening to their feedback tones wax and wane based on the strength of the filtered EEG signals. Then a "ding" sounded and the tones stopped. For the next 8 seconds, the monitor displayed color-coded numerical feedback of their alpha brain-wave integrated amplitude..."

In order to capture any "positive psychological results by reducing anxiety and other psychopathology" a pre and post battery of four well known measures was recorded, the Minnesota Multi-Phasic Personality Inventory, the trait forms of the Multiple Affect Adjective Check List, Clyde Mood Scale, and Profile of Mood States.

This short but unclear paper highlights the differences between research done to validate a commercial clinical intervention and a pure experimental research design. There was no control group included, in this 'Non-blinded' 'Within Subject' design and very little information was given about the protocol and none about the EEG measures or how they related to the psychometric

measures. Somewhat oddly, Information was given on the length and material of the electrodes but not on why the electrode locations were chosen or the technical details of the EEG recordings.

This was a time consuming study where each trainee spent 10-12 hours at the training centre each day for 7 consecutive days and did neurofeedback training for around 9 to 14 hours.

But still, despite these short comings the majority of psychometric measures did show a highly statistically significant improvement.

#### **3.7.11. Wang, 2013**

In a two part study, Sheng Wang, Yan Zhao, Sijuan Chen, Guiping Lin, Peng Sun and Tinghuai Wang (2013), first selected 24 high and 24 low trait anxiety participants from a pool of 358 undergraduate students using the Chinese version of the State-Trait Anxiety Inventory. They then recorded event related potentials (ERP) of the 48 participants while they performed an Emotional Stroop task.

The Emotional Stroop task is a variation of the well-known colour Stroop task, where the word for a colour and the colour of the “ink” the word is written in can be either, congruent (i.e. the word “red” in red ink) or incongruent (i.e. the word “red” in blue ink) In different trials participants are instructed to push a button to identify the colour of either the ink or the word. Many studies have shown that participant’s reaction time increases in the incongruent trials and this is known as the Stroop effect. In the Emotional Stroop task, participants must identify the colour of the text of three different emotional categories of words (negative, positive and neutral). The suggestion is that highly anxious people tend to have

a negative bias and focus more on negative stimuli and therefore have a slower reaction to the negative words in the Stroop task.

Event related potentials of the brain are computed by recording the electrical response of the brain to hundreds of trials and then averaging the trials to cancel out the background noise of brain processing that is not related to the task. This leaves the brain response specifically associated with identifying the stimuli and responding to the task. ERPs have excellent temporal resolution and look at brain activity in time windows of around 500 milliseconds. The ERP Brain response to stimuli is characterised by positive and negative fluctuations at different times in relation to a baseline period just before the stimuli. So for example a well-known ERP is called the P300 and is a positive deflection at around 300 milliseconds after a stimulus is presented to a person.

Wang et al. showed that in the high trait anxiety participants only, there was a significant main effect of increased reaction time to negative words. The ERPs also showed longer latencies and increased amplitudes for the P300.

In the second 'Single-blinded', 'Between Subject' study design, the 24 high trait anxiety participants were randomly assigned into one of two groups; either EEG feedback group (n. =12), or sham feedback group (n. =11).

The training consisted of one continuous 27 min session, twice a week for a total of 15 sessions. The feedback was measured from C3 or C4 and the alpha activity (8–13Hz) varied the volume of an 'ocean waves' sound also when the alpha was over a threshold set to a range of 0.7 to 1.5 times the baseline average, a 'warble' sound played.

Again, no training or pre vs. post EEG data was reported but more meaningfully there was a significant reduction in the P300 latencies and also reduction in reaction time for negative words on the emotional Stroop test for the neurofeedback but not the sham group.

### **3.7.12. Ramirez, 2015**

In a 'Non-blinded', 'Within Subject' pilot study Rafael Ramirez, Manel Palencia-Lefler, Sergio Giraldo and Zacharias Vamvakousis (2015) trained a multi-channel EEG protocol intended to increase both arousal and valence in an elderly depressed population. Arousal was calculated as the frontal beta to alpha ratio (i.e.  $(\text{beta of F3} + \text{F4} + \text{AF3} + \text{AF4}) / (\text{alpha of F3} + \text{F4} + \text{AF3} + \text{AF4})$ ) and Valence as frontal Alpha asymmetry ( $\text{F4 alpha} - \text{F3 alpha}$ ). The EEG was collected with a cheap consumer device and custom software.

In 10 sessions (2 per week) of 15min each, participants chose a set of 5 or 6 music pieces and their arousal and valence would affect the loudness and tempo of the notes of the music, to make it sound "happier" as they moved towards a more positive mood.

Ramirez explained: "The system consisted of a real-time feedback loop in which the brain activity of participants was processed to estimate their emotional state, which in turn was used to control an expressive rendition of the music piece. The user's EEG activity is mapped into a coordinate in the arousal-valence space that is fed to a pre-trained expressive music model in order to trigger appropriate expressive transformations to a given music piece (audio or MIDI)."



The Beck Depression Inventory was used as the main pre vs. post measure of change and was claimed to show a statistically significant reduction in depression. But the data was only of 5 people and not a lot of confidence can be given to these claims. Arousal and valence scores are given of the session data, but with the information given it is difficult to make any conclusions.

The sonification system looks very interesting but insufficient evidence of its utility was presented. Clearly they were working with a difficult population with many health issues; however the minimum expected data from a pilot study of this nature would be some user feedback to establish if this elderly depressed population enjoyed the music manipulation or found that having their favourite tune that they have known and loved for years tampered with was disconcerting.

### **3.7.13. Summary of EEG Sonification neurofeedback studies**

Whilst it is interesting to see that neurofeedback started with sound based feedback and the first published neurofeedback study was in 1970 and used sonification, it is striking to note the lack of research papers in the 1980s and 1990s, despite the 1990s being the decade of the brain and showing a massive increase in all areas of brain research. This of course does not mean EEG sonification was not being used clinically.

This could well be due to the introduction of digitisation of the EEG and advances in computer displays in the 80s, that allowed real-time EEG to be displayed on a computer monitor, instead of the old analogue pen on papers systems and allowed more complicated analysis. As a consequence of these

advances most neurofeedback systems focused on visual displays, relegating sound feedback to a secondary role and this is still the case today.

Although this handful of studies are encouraging in that they show that it is possible to make a change in people's EEG band power and psychometric measures with just one session of real-time EEG sonification feedback, they do not constitute a substantial body of work in support of the claim that real-time EEG sonification neurofeedback 'works' or has a lasting behavioural benefit.

**Table 3.7.13** Summarises the research designs used in the 12 EEG sonification neurofeedback studies reviewed in this section.

Name:	N.	Participants:	Se.	Dur.	Design:
<b>Nowlis 1970</b>	26	Healthy	1	c. 30	Within Sub. Train high and low alpha
<b>Schwartz 1976</b>	20	Healthy	1	3 * 9 m	Within Sub. 3 * Alpha asymm: Low-Low, High-Low, Low-High
<b>Hardt 1978.</b>	8/8	Highest vs. Lowest anxiety	7	32/16 m	Between: No Control Highest vs. Lowest anxiety
<b>Allen 2001</b>	9/9	Healthy women	5	5 * 6 m	Between: Alpha Asymmetry: Left up vs, Right up
<b>Fell 2002</b>	13	Healthy	1	23 m	Within Sub. 1 Control Subject
<b>Hinterberger 2011</b>	10/10	Experience vs. Non-Meditation	1	15 m	Between: No Control
<b>Choi 2011</b>	12/11	Depressed patients	10	6 * 4 m	Between: Real vs. Psychotherapy placebo
<b>van Boxtel 2012</b>	18/12/20	Healthy	15	24 m	Between: Real vs. Sham Random Beta vs. No Feedback
<b>Hardt 2012</b>	40	Healthy	7	76 to 120 m	Within Sub. No Control
<b>Wang 2013</b>	12/11	High anxiety	15	27 m	Between: Real vs. sham
<b>Ramirez 2015</b>	6	Depressed elderly	10	15 m	Within Sub. No Control
<b>Hinterberger 2016</b>	36	Experience vs. Non-Meditation	6	6 * 20 m	Within Sub. 3 intervention, 3 control

**Table 3.7.13:** Shows 12 EEG Neurofeedback Sonification papers by year. N. = the number of participants in the study; Participants: = type or nature of participants; Se. = number of sessions; Dur. = Duration of session; Design: = the type of experimental research design used in the study.

The studies had a total of 301 participants with a range of between 6 to 50 people and an average of 24 participants per study for the 'within subject design' and 11 per group for the 'between' designs. On average each person did 7 sessions (range 1 to 15) of 40 minutes (range 15 to 120 m) (The between subject design: 9 sessions of 28 minutes and for the within subject design: 4 sessions of 51 minutes) meaning each participant did around 4 hours of training and each study took an average of 132 hours of just the neurofeedback or control intervention phase, not including the assessments. Four studies did only 1 session with an average of 19 participants of 24 minutes, making a total of 8 hours of sessions.

Eight of the studies used healthy participants', two used anxious people and two depressed patients.

The most popular electrode location was the central motor strip (C3, Cz, C4) with 5 studies, followed by frontal sites (F3, Fz, F4) with 4 studies and Occipital sites (O1, Oz, O2) with 3. The number of electrodes used range from 1 to 4 with an average of 2.

All 12 studies trained alpha activity of which 4 were alpha asymmetry and 3 trained other EEG bands as well. 4 of the alpha studies train to increase alpha and one train to both increase and decrease alpha power. Two of the alpha

asymmetry studies trained to increase alpha on the right (i.e. decrease activity) only and two trained both up and down. Only the van Boxtel and Schwartz studies used implicit neurofeedback and the rest explicitly asked the participants to try and modify their brain waves. This is potentially a significant observation but as there are so many differences between each of the studies, no conclusions can be drawn about implicit versus explicit instructions and learning outcomes from these sonification neurofeedback studies.

Six of the studies used a 'within subject design' with participants doing multiple sessions of different protocols and six used a 'between subject design' with different participants in each group. Nine of the studies have at least one control group and 3 had a fake feedback or sham group. Four studies had a Single-blinded intervention group and only the van Boxtel, study had a double-blind experiment design with sham feedback and no feedback control group.

Name:	Sonification:	Ch.	EEG	Measures:
<b>Nowlis 1970</b>	Threshold of tone	2	Oz-Fz or Oz-Cz: Alpha	Baseline/On/Off Alpha: interview
<b>Schwartz 1976</b>	Threshold of tone	2	P3 – P4: Alpha symmetry	Alpha Power, Self-report on cognitive strategy
<b>Hardt 1978</b>	AM of tone	3	Oz, O1, C3: Alpha, linked ears	Per/Post Alpha & Mood scales MAACL
<b>Allen 2001</b>	Threshold over vs. under tone	2	F3, F4, Alpha asymmetry	Emotion responses to film clips: EEG asymmetry, facial EMG, Self-report,
<b>Fell 2002</b>	FM-inverted	1	Cz: Alpha	Per/Post Alpha Power
<b>Hinterberger 2011</b>	AM & FM MIDI	1	CPz: Alpha, USP, SCP, Delta, Theta, ECG	Self-rating: contentment, relaxation, happiness, inner harmony
<b>Choi 2011</b>	AM of music	2	F3, F4, Alpha asymmetry	Daily Stress, ATQ-P, ATQ-N, Beck Depression Inventory, Semantic Fluency Test, Phonological Fluency, Stroop Test, Hamilton Depres. Inven.
<b>van Boxtel 2012</b>	high-pass filter - user selected music	2	C3 & C4 Alpha	Per/Post: qEEG, ERP, POMS Negative Mood, Quality of life, Dutch WHOQoL-bref Sleep questionnaire, Guided interviews
<b>Hardt 2012</b>	AM of tone	4	O1, O2, C3, C4 Alpha activity	EEG, Minnesota Multi-Phasic Personality Inventory Multiple Affect Adjective Check List, Clyde Mood Scale Profile of Mood States
<b>Wang 2013</b>	AM of wave sound, Plus Threshold	2	C3 & C4 Alpha activity	State-Trait Anxiety Inventory, RT & ERP of Emotional Stroop task
<b>Ramirez 2015</b>	loudness & tempo of Music notes	4	AF3, AF4, F3, & F4, Alpha asymmetry beta/alpha ratio	Beck's Depression Inventory Arousal & Valence
<b>Hinterberger 2016</b>	AM & FM MIDI	1	CPz – multi-Bands EEG, ECG	Self-rating: well-being, perception, and life-spirit

**Table 3.7.14:** Shows the type of sonification, the number of EEG channels and electrode locations, the physiology measures that were trained and the psychometric outcome measures used in each study. Sonification: = the type of sonification; Ch. = number of EEG channels; EEG: = The Scalp location the EEG was recorded from and frequency bands trained; Measures: = Psychometric assessments.

Looking at the outcome measures in [Table 3.7.14](#), Fell (2002), only measured the EEG parameters, Hinterberger (2011; 2016) made up their own well-being questionnaire. The others used a range of questionnaires about mood and depression, like the Beck Depression Inventory, Spielberger State-Trait Anxiety Inventory, Minnesota Multi-Phasic Personality Inventory, Profile of Mood States, Two studies used the Stroop task, two recorded ERPs and two conducted interviews and one asked about the cognitive strategies the participants used in training.

Eight of the studies analysed the session EEG data and only 5 looked at the pre and post EEG changes and surprisingly 3 did not look at the EEG measures at all. All of the nine studies that looked at the EEG showed change in the training group.

Reviewing the sonification methods used in these studies, the earliest studies used a simple threshold strategy where a tone would play when the EEG was over a set value. Five studies used this technique. The threshold technique is on the border of being considered a sonification as it provides very little information about the on-going EEG activity and could more accurately be considered an alarm, but it was included as it is the earliest examples of neurofeedback, 42% of the studies use it and the studies showed effective results. The most popular technique was amplitude modulation (AM) with seven studies, three of which used a simple tone and the others combined with other techniques. Frequency modulation was used in four studies and five studies had a mixture of techniques, so for example Wang et al. 2013 used AM of a “wave” sound plus a threshold to play a “warble” sound and van Boxtel (2012) did an AM modulation of a high pass filter of pre-recorded music. Ramirez (2015)

made the most complex and interesting sonification technique, using a music generation engine to manipulate the loudness and tempo of individual notes in a score. But it seems the better and more complex the sonification the less rigorous the study.

Some studies asked what the participants thought of the sonification sessions but none of them made any direct measures of the sonification ability to convey the EEG data and only Hinterberger 2016 made a comparison between two different sonifications. These two sonifications had at least 30 sound generation components and were triggered by 8 different EEG frequency bands and included heart rate parameters and a coloured light feedback, so it is not really possible to make any meaningful conclusion about the differences between the two sonifications alone.

In summary, there are some very interesting and promising findings in these sonification neurofeedback studies as all studies claimed an improvement in psychometric or EEG measures or both. But overall the research methods were quite weak and rather disappointingly insufficient statistical data was given to allow any meta-analysis to be performed. This supports the observation that the majority of these papers were pilot studies. Although these studies will not have been very expensive as EEG equipment is relatively cheap and the protocols were all quite simple, they still represent hundreds of hours of data collection.

Most disappointing of all was the lack of discussion or investigation into the sonification techniques themselves. None of the papers discussed if the sonifications were matched in any way to the nature of the data, number of channels being used or the condition being trained. Most of the

neurofeedback studies use the simple sonification techniques discussed in [section 3.5.3](#) and no attempt was made to quantify their ability to convey the data.

### **3.8. Conclusions and Implications of Research:**

This chapter started with the first example of EEG sonification from 1934 and gave an overview of the 145 research papers found from the last 83 years. [Figure 3.3.1](#) shows that there has been a significant increase in the number of papers published each year since 2004. But the majority of these have been conference papers and proof of concept studies. So the domain of EEG sonification must still be considered in its infancy.

[Section 3.4](#) highlights two important continuums that create six subdomains of the EEG sonification field. The temporal continuum distinguishes between sonifications that can transform the data into sound in real-time and those that require extended processing or data averaging. The qualitative to quantitative continuum distinguishes between sonifications designed, primarily for aesthetic purposes and those more concerned with the fidelity of the data transformation.

[Section 3.5.1](#) reported on a data sonification “design space map” that is intended to aid the design decisions when making a new sonification and identifies three divisions: Discrete-Point, Continuous and Model-Based sonification, that are categorised by the number of data points and dimensions in the dataset.



**Section 3.5.3** identified 21 sonification techniques found in the literature and parses them into the three space map divisions.

**Section 3.6** explored the methods that have been used to assess an EEG sonification's ability to convey the EEG data. Despite some assessment techniques showing the utility of some of the sonifications, none found in the EEG sonification literature are capable of assessing the full temporal dynamics of the EEG signal. This indicates the need to develop and validate an alternative assessment tool.

In the final **Section 3.7** a summary of 12 EEG sonification neurofeedback studies was presented. Tellingly only six of the 22 sonification techniques that have been found that are capable of conveying real-time EEG have been used in a neurofeedback study, and these have mostly been the simpler techniques. This could be taken as evidence that running a full on neurofeedback study is very time-consuming and highlights the need for a suitable real-time assessment tool that could provide preliminary evidence of a sonification's comparative ability and it's suitability to go forward to a full neurofeedback study

Therefore this research is not about finding or developing the “perfect” sonification for EEG per se, as there will be a multitude of different applications with their own unique requirements. But it is about developing and validating a methodology and assessment tool, which is specific to the needs of the EEG data and could aid in the development of a sonification tailored for a particular EEG task.

## Chapter 4: Experiment 1

### Prototyping a Method for the Assessment of Real-Time EEG Sonifications

#### 4.1. Introduction

As noted in the previous two chapters, one aim of this research is to establish whether sonification is suitable for use in neurofeedback (for example, in situations where the eyes are closed or needed elsewhere). A second aim is to explore what needs to be taken into account for successful applications of sonification in neurofeedback. One point of particular relevance to these aims is that learning theory suggests that the more **rapidly** and **accurately** EEG information can be fed back to a participant, the more efficient any resulting learning will be. At the same time, human hearing is a rapid channel of communication and has a higher temporal resolution than human vision (See section 2.3.4, page 78). These points taken together suggest that sonification may have valuable potential for neurofeedback.

The above considerations suggest that a useful first step would be to investigate how to assess the ability of sonifications to convey the **rapid** and **temporally complex** EEG data for neurofeedback with sound. This chapter reports on an empirical investigation into one possible mode of assessment, the tracking of an audio signal with a mouse.

In this first experiment, participants were asked to listen to the sound of the sonified EEG and try and track the activity that they could hear by moving a slider on a computer screen using a computer mouse. To allow for replication

and a within-subject study design, pre-recorded EEG data was sonified and played back at real-time speed.

#### **Experiment 1 research questions:**

**EQ4.1).** Can the continuous tracking of a real-time EEG sonification with a computer mouse and slider on a computer screen, be a practical assessment tool from the point of view of both the experimenter and participants?

**EQ4.2).** Can the continuous tracking of a real-time EEG sonification with a computer mouse and slider on a computer, provide quantitative information about how well a sonification can convey the real-time EEG data?

**EQ4.3).** Can the relative ability of a sonification to convey the EEG data be assessed by comparing two sonifications on the same tracking task?

Motivation for this experiment

As explained in [section 2.2](#) the objective of neurofeedback is to enable the modification of one's own brain activity through feedback of one's own EEG, and the primary aim of this experiment is to develop and test a method to assess the efficacy of this feedback.

Although real-time feedback is critical in the neurofeedback loop, and the sonifications in this experiment were specifically selected for this ability, in order to make a controlled comparison between the different sonifications, pre-recorded EEG was used. Furthermore, in order to have an objective measure of how well the real-time changes in activity levels could be continuously

perceived, participants were asked to track the activity in the sonification with a slider on a computer using a mouse. Thus if they perceived the Amplitude or Frequency of the sound to increase they were instructed to move the slider up and if either went down they had to move the slider down. The tracking data was then correlated with the original EEG data that was used to create the sonification to create a tracking accuracy score.

Clearly, having to make a motor response to such a rapidly fluctuating signal introduces a great deal of lag, and degrades performance. However this lag will apply equally to all sonification techniques in a head-to-head comparison and averaging or smoothing of the data to slow it down and make it more track-able is likely to reduce the information content and degrade perception of the finely detailed signal. Of course in the final neurofeedback applications, participants will not need to make a motor response, but only a mental response to the sonifications.

In order to try and disambiguate the effort of listening to the sonification from the effort of tracking the sonification, a six factor workload questionnaire was administered after each sonification trial. Also to see how people felt about the sound of the sonification two questions about the perceived arousal and valence of the sound were asked after each sonification listening trial. In order to try and control for musical experience four questions were asked at the end of the study about musical education and experience of playing an instrument.

#### **4.1.1. Sonification Assessment Method**

As discussed in [chapter 3](#), some earlier EEG sonification studies have used the 'two-alternative forced-choice' (2AFC) assessment method, where the

participant is repeatedly presented with a sonification from one of two groups, e.g., patient with epilepsy versus a non-patient (Loui et al., 2014), or patients suffering from mild cognitive impairment versus healthy age-matched controls (Vialatte et al., 2009, 2012; Wu et al., 2009). In such studies, after some initial training, participants are asked to pick which group a particular sonification file belongs to. Some of these studies have shown very good detection accuracy, demonstrating that people are able to perceive differences in the EEG data when it has been sonified but this assessment method does not really capture the temporal aspects of the perception of the sonified data.

By contrast, some studies maintain some of the temporal information by getting participants to identify the onset of a particular EEG activity. So, for example, Khamis (2012) played two channels of EEG sonification of patients with temporal lobe epilepsy and asked the study participants to push a button when they heard the onset of seizure activity. Khamis concluded "With only 2 hours of training, non-expert subjects can detect seizures from audified EEG signals of 2 electrodes with a comparable degree of accuracy as can be done visually from a review of EEG traces using the 10-20 electrode placements by an expert electroencephalographer".

From the point of view of assessing the temporal resolution of a sonification this is an improvement over the 2AFC method, but still does not capture the full range of dynamic characteristics of listening to continuous sound-based feedback.

Thus the development of a methodology (or set of methods) that could assess the ability of sonifications to convey in real-time, temporally rich EEG data

would greatly assist the design and selection of appropriate sonifications for a range of application areas such as neurofeedback, surgical monitoring, or brain computer interfaces (BCIs) (Curran, 2003). (See section, 3.6 on the 'Assessment of EEG Sonification' and 4.2.4. Measure1: Quantitative – Tracking)

#### 4.1.2. Choice of Sonifications

In the design of sonifications to present EEG data, in order to maximize information transmission, perception and learning, a balance must be struck between converting as much of the complexity of the EEG data as possible into sound and between a person's ability to perceive and utilise the signal in the sound. By Hermann's definitions for sonification (Hermann, 2008) (see [section 2.3.1](#)), the data transformation into sound must be objective, systematic and reproducible; at the same time, the purposes of neurofeedback require real-time sonification to render the time series data features in a salient, immediate, and contingent fashion (Collura, 2014).

To date, there has been a wide range of different data processing and sonification techniques used to display EEG with sound, but few studies have tested sonifications against each other for their ability to convey the temporal dynamics of the EEG signal. This study is an initial step towards establishing and validating a method for comparing EEG sonifications appropriate for neurofeedback. Thus it seemed prudent and logical to start with the simplest of sonification mappings to establish a "baseline" that more complex sonifications can be tested against.

**Audification** is perhaps the simplest form of sonification mapping, in the sense that it simply maps the input data to sound pressure levels. This could be

thought of as the auditory equivalent of looking at a raw EEG trace. However, because 98% of the EEG power is below 30 Hz (Kropotov, 2010), simple real-time audification would produce results below the human auditory range. Thus, most Audifications compress time by speeding up the data presentation between 20 to 200 times and therefore this can't be done in real-time. Possibly the next simplest sonification able to display EEG in real-time would be Amplitude Modulation.

**Amplitude Modulation (AM)** sonification could be seen as analogous to the bar graph of a band power used in a typical neurofeedback display, as the power of EEG band increases, the bar graph goes up and so does the volume of the sound. Conceptually AM sonification is simple (though this is no guarantee of perceptual simplicity). But despite the simplicity, it is not obvious how well this mapping might allow listeners to track rapid changes of the kind typical of EEG and this is a matter to be established empirically.

**Frequency Modulation (FM)** sonification maps changes in the amplitude of the EEG to changes in the frequency of the sound output. Frequency has obvious potential for communicating relatively rapid and fine changes in real-time, but again, it is unclear how well this mapping might be suited to the particular purposes of conveying EEG data.

Because of the conceptual and technical simplicity of the AM and FM mapping, the only subjective design decisions needed are to select the carrier wave frequency for the AM sonification, and the output frequency range for the FM sonification. In piloting prior to this study both were simply chosen to fit comfortably within the human auditory frequency range.

Thus, Amplitude Modulation (AM) and Frequency Modulation (FM) sonifications were the first two continuous data representation parameter mapping methods chosen for comparison in this first experiment. By starting with these conceptually simple, easy-to-generate sonifications that require a minimum of subjective design decisions, the intention is to establish an initial baseline measure. Such a measure has the potential to facilitate comparison of more complex and engaging sonifications. The use of open source research presentation and sound synthesis software will allow other researchers to replicate and extend this method on other sonifications.

This first experiment would form an empirical basis to build on and since the experiment uses both subjective and objective tracking measures, ample scope would remain for contrasts between findings: for example, a better tracking score could come from a sonification with a worse subjective rating in terms of task load, emotional ratings of valence and arousal, or aesthetic quality of the sound.

#### **4.1.3. Choice of EEG parameter**

There are a large number of parameters that can be derived from the raw EEG including the power of subdivisions of the frequency range called frequency band power, e.g. alpha and beta; the ratio between the EEG band power, e.g. Theta/Beta ratio; the coherence or phase between different electrode locations and complexity measures of the EEG such as sample entropy. However in neurofeedback it is common to train only a few band powers.

As was presented in [section 2.1.9](#) the alpha frequency band is a large amplitude signal that is relatively easy to measure and has some interesting



temporal dynamics that could be interesting to sonify. Furthermore it has well-known cognitive concomitance (see [section 2.1.9](#)) and has been used in a large number of neurofeedback studies as well as EEG sonification neurofeedback studies (see [Table 3.7.14](#)).

Thus the EEG alpha band was selected for this experiment.

## **4.2. Research Methods**

### **4.2.1. Electroencephalogram Stimuli**

Six, 3 minute, 19 channels "Full Cap" EEGs were recorded in two conditions, eyes closed and eyes open, using the author as a participant. The EEG was recorded with a Mitsar 202 amplifier and WinEEG software (Mitsar Co. Ltd.) at a sample rate of 2000 Hz and saved at 500 Hz, 24 bit resolution, in a linked ears referential montage. The low cut filter was set to 0.53 Hz and the high at 50 Hz, the notch filter was 45 to 55 Hz and all impedances were kept below 5 kilohms. In Matlab 11b (Matlab Ltd.) the EEG was band-pass filtered with a fifth Order Butterworth IIR filter, to make two EEG bands, one of low alpha (LA) 7-10 Hz, and the other of high alpha (HA) 10-13 Hz and the Hilbert transform was used to extract the amplitude envelopes of alpha EEG signals.

Alpha activity generally increases when sensory information is reduced to the brain. For example, when the eyes are closed, more alpha is produced in the occipital cortex in the back of the head. Consequently, the 'eyes closed' condition is typically a lower arousal state than 'eyes open' and generally has more alpha activity in most people (Kropotov, 2010). Traditionally, alpha has

been defined as a band of 8 to 12 Hz, but newer research suggests that the upper and lower alpha bands represent different cognitive functions (Klimesch et al., 1998). The electrode location Pz in the back of the head was selected because it has a good level of alpha activity and is commonly used in neurofeedback for relaxation training.

Four 1 minute files were selected that captured a selection of typical alpha activity in eyes closed and eyes open and in the High and Low Alpha frequency conditions, by a visual examination of the raw alpha signal and spectral content.

The remainder of this section will consider the characteristics of these four sample EEG files used for this experiment, as summarised in [Table 4.2.1](#).

In [Table 4.2.1](#), the names of the EEG files are;

- **'HAO' is the high alpha band in the eyes open conditions state.**
- **'HAC' is high alpha with eyes closed.**
- **'LAO' is low alpha with eyes open and**
- **'LAC' is low alpha with eyes closed.**

The contents and meaning of the columns in [Table 4.2.1](#) are as follows: 1) the number of alpha bursts, quantified as alpha activity over the grand mean for longer than 280 ms; 2) the mean duration of the alpha bursts in seconds; 3) excess kurtosis of the alpha amplitude envelope (which is a measure of the pointedness or flatness of the histogram of the distribution - the smaller the number, the closer to a normal distribution and the less pointed the peak - negative values indicate flatness of the peak); and 4) the skewness (which is a

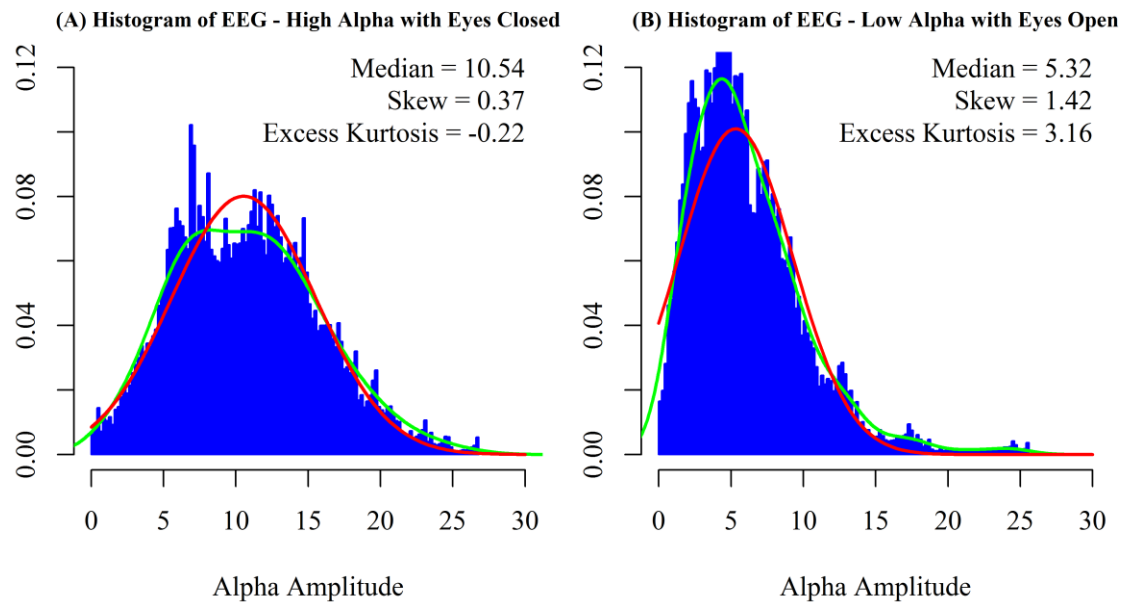
measure of how symmetrical the distribution of the data is around the mean, and the distribution of the 'tails').

Considering [Table 4.2.1](#) overall, although there is a clear visual difference in these sample files in the patterns of alpha amplitude envelope activity between the eyes open and eyes closed conditions, the number of alpha bursts and the mean duration do not show a large difference.

The eyes-open alpha EEG had a high excess kurtosis distribution (i.e. high peakedness or leptokurtic) and is more positively skewed, compared to the eyes closed EEG, suggesting the eyes open EEG has fewer and shorter large amplitude "bursts". The eyes closed alpha EEG was closer to a normal distribution on both kurtosis and skewness with a flatter peak of distribution implying more mid-range activity.

	# of alpha bursts	Mean duration alpha bursts [s]	Excess kurtosis	Skew
<b>HAO</b>	35	0.60 [0.33]	0.75	0.98
<b>HAC</b>	40	0.57 [0.38]	-0.22	0.37
<b>LAO</b>	38	0.51 [0.19]	3.15	1.42
<b>LAC</b>	35	0.58 [0.31]	0.23	0.69

**Table 4.2.1:** Quantification of alpha activity in four EEG files; '# of alpha bursts' gives the number of 'bursts' of alpha which are short duration of large amplitude activity.



**Figure 4.2.1:** Normalized Histograms of the EEG alpha activity: (A) left panel: the High Alpha, Eyes Closed and (B) right panel: the Low Alpha Eyes Open. The green line is the frequency density estimate of the EEG data, the red line represents the normal distribution with the same mean and standard deviation as the data.

#### 4.2.2. Sonifications of the Electroencephalogram

Alpha signal envelopes were imported into Pure Data software (Puckette, 2002) where any EEG values greater than 30 microvolts (mV) were set to 30 mV, to exclude artifacts like eye blinks and muscle tension, so that the data values ranged between 0 and 30 mV. The audio sample rate was set to 48,000 Hz (48 kHz was chosen to give an integer multiplication of the 500 Hz EEG sample rate i.e. 96) and the four 1 minute EEG files were sonified with AM and FM-based methods. Two different audio frequency outputs were chosen for the carrier wave to control for any bias in the hearing or aesthetic response of the participants. Each carrier frequency was presented in 4 sound files to

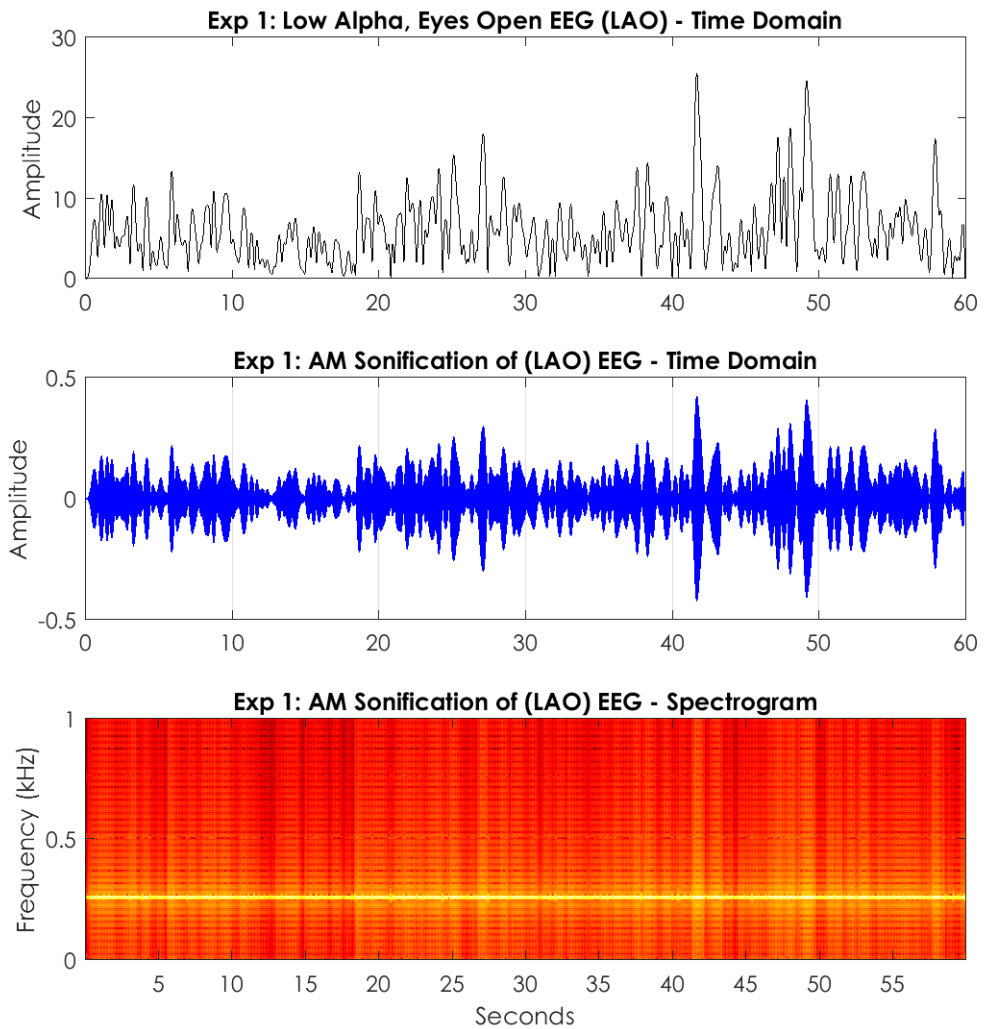
counterbalance across conditions of eyes open and closed and high and low alpha.

#### 4.2.2.1. AM Sonification

For AM sonification, each data point was divided by 30 to scale the values to range between 0 and 1. The data was then linearly interpolated to match the EEG to the audio sample rate. Half of the files were then multiplied by a sine wave carrier of either, 261.6 Hz (Middle C) or 523.2 Hz and the output saved as a .wav file.

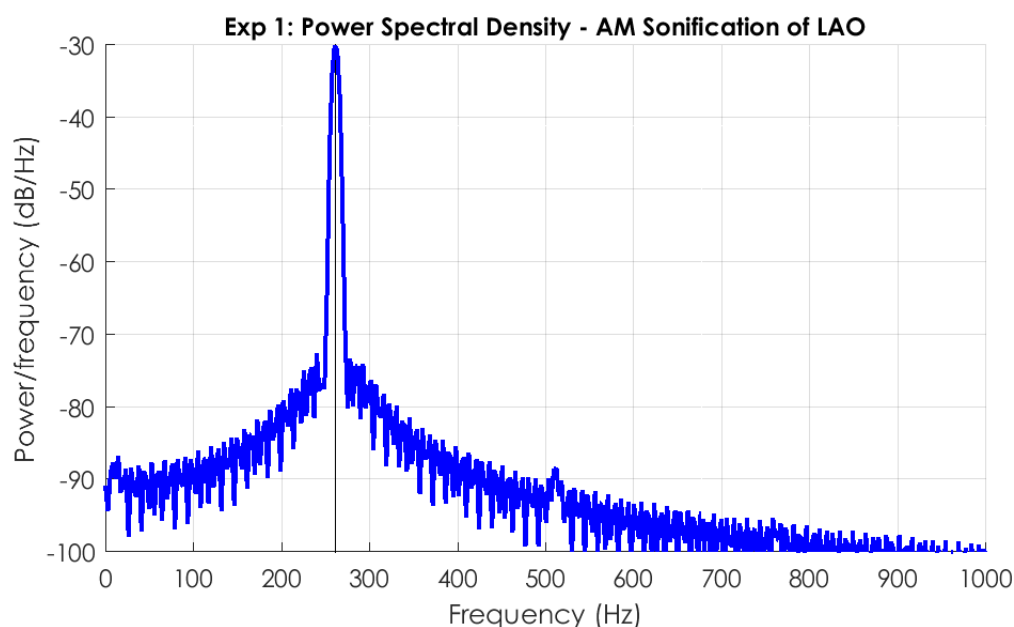
In [figure 4.2.2.1.1](#), the top subplot shows a time domain of the original Alpha EEG for the low alpha with eyes open (LAO). The amplitude values range from 0 to 30  $\mu V^2$  on the Y axis and for 60 seconds on the X axis. The middle subplot shows the time domain of the sound output from the AM sonification with the 261.6 Hz modulation frequency. It can clearly be seen that the peaks and troughs of the EEG, match up with the peaks and troughs in the sound file.

The bottom subplot shows the spectrogram, time frequency plot of the sound output of the same AM sonification. (The spectrogram is not a very appropriate plot for the AM signal, because as can be seen by the yellow line, the 261.6 Hz modulation has a constant frequency and it is only the 'bleeding' by the high amplitude signals that show where the peaks of activity in the EEG are. However, it is shown for comparison as it will be useful for the FM signal in the next section).



**Figure 4.2.2.1.1:** Shows the original Alpha EEG (LAO) in the top subplot. The sound output from the AM sonification with the 261.6 Hz modulation frequency in the middle and the spectrogram of the same, is shown on the bottom subplot.

**Figure 4.2.2.1.2**, is a plot of the spectral characteristics of the AM sonification of LAO and shows a peak of activity around 261.6 Hz (vertical grey line). There is a very small harmonic at 523.2 Hz but otherwise the vast majority of the amplitude of the sound is at around 261.6 Hz.

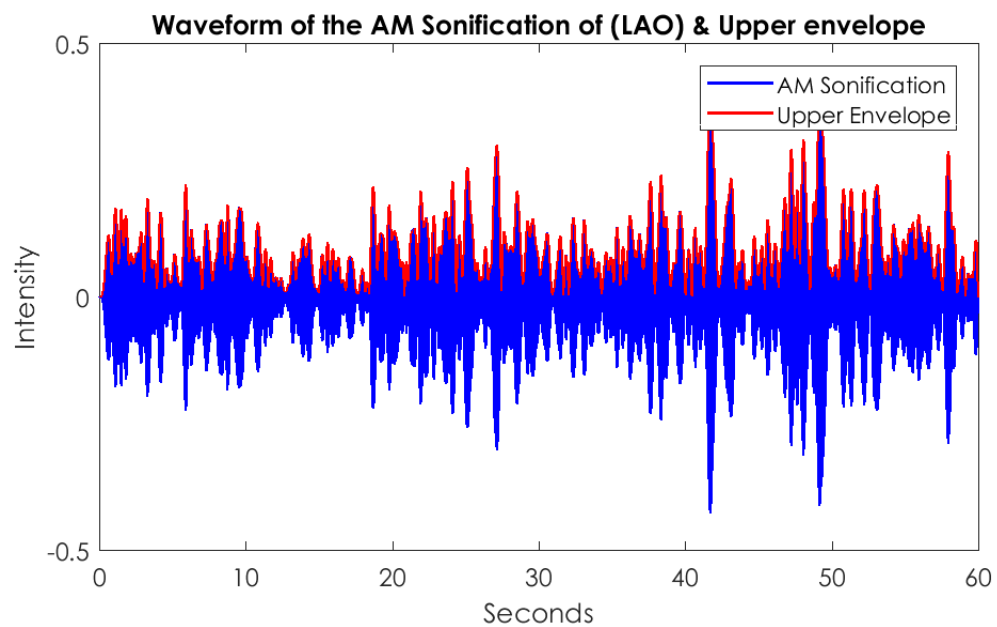


**Figure 4.2.2.1.2:** Shows the Welch Power Spectral Density Estimate of the AM Sonification of low alpha with eyes open (LAO).

In order to verify the accuracy of the sonification process, the correlation between the original EEG data and the sound of the AM sonifications was computed. The cross correlation function requires the two data sets to have the same number of data points in length. The EEG was sampled at 500 Hz so the one minute file had 30000 data points; however the sound file had a sample rate of 48 KHz making it 2,880,000 data points long. In Matlab the EEG files were Spline Interpolated using the 'interp1' function, so for each EEG data point, 96 new data points were added.

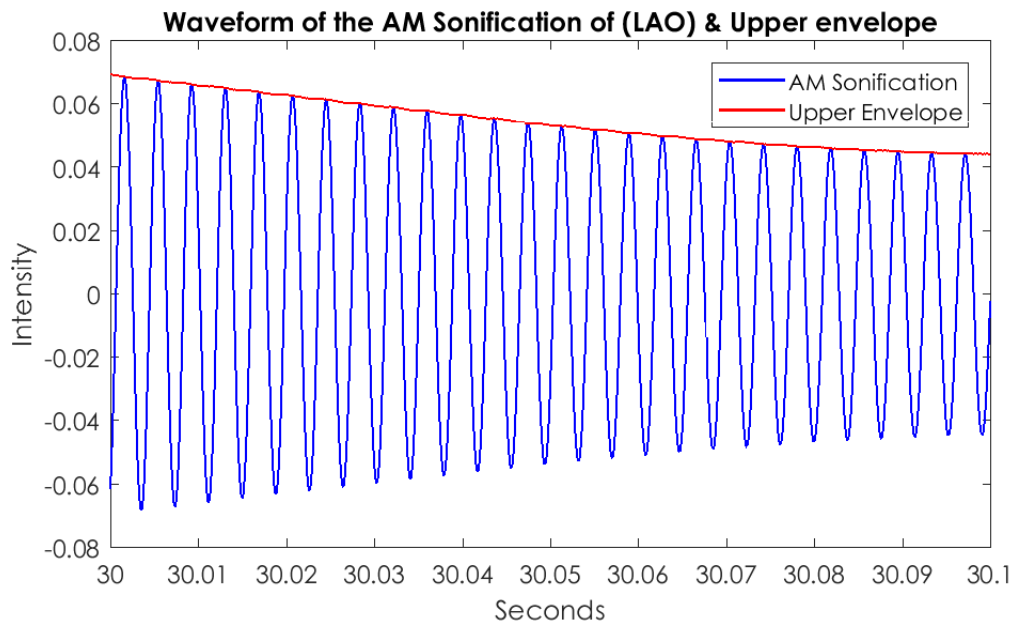
For the AM sonification the sound data oscillates from positive to negative around the zero line at the carrier frequency of 261.6 Hz, but the EEG data is represented by the amplitude envelope of the sound. In Matlab the upper

'envelope' of the sound was extracted with the `'[yupper, ylower] = envelope(x)'` function which uses a Hilbert transform to filter out the high frequency component of the signal and find the 'outer edge' of the signal. [Figure 4.2.2.1.3](#), shows the sound data in red and the upper envelope in blue and [figure 4.2.2.1.4](#) shows a close-up of 100 milliseconds where the blue line can be seen marking the upper edge of the sound data.



[Figure 4.2.2.1.3](#): Shows the sound of the AM sonifications (blue) and the upper envelope (red) extracted using Hilbert transform.





**Figure 4.2.2.1.4:** Shows 100 milliseconds of the AM sonifications (blue) and the upper envelope (red)

Because the sonification technique could potentially introduce a time lag between the original EEG signal and the sound output, the cross-correlation, `'[corr, lags] = xcorr(EEG, Sound, 'coeff');'` function in Matlab was use to check for correlations at all-time points, both positive and negative, across the whole one minute file and all maximum cross-correlations were at a time lag of 100 ms or less (i.e. this is within the impulse response of the fifth Order Butterworth IIR filter use used to generate the Alpha EEG envelope).

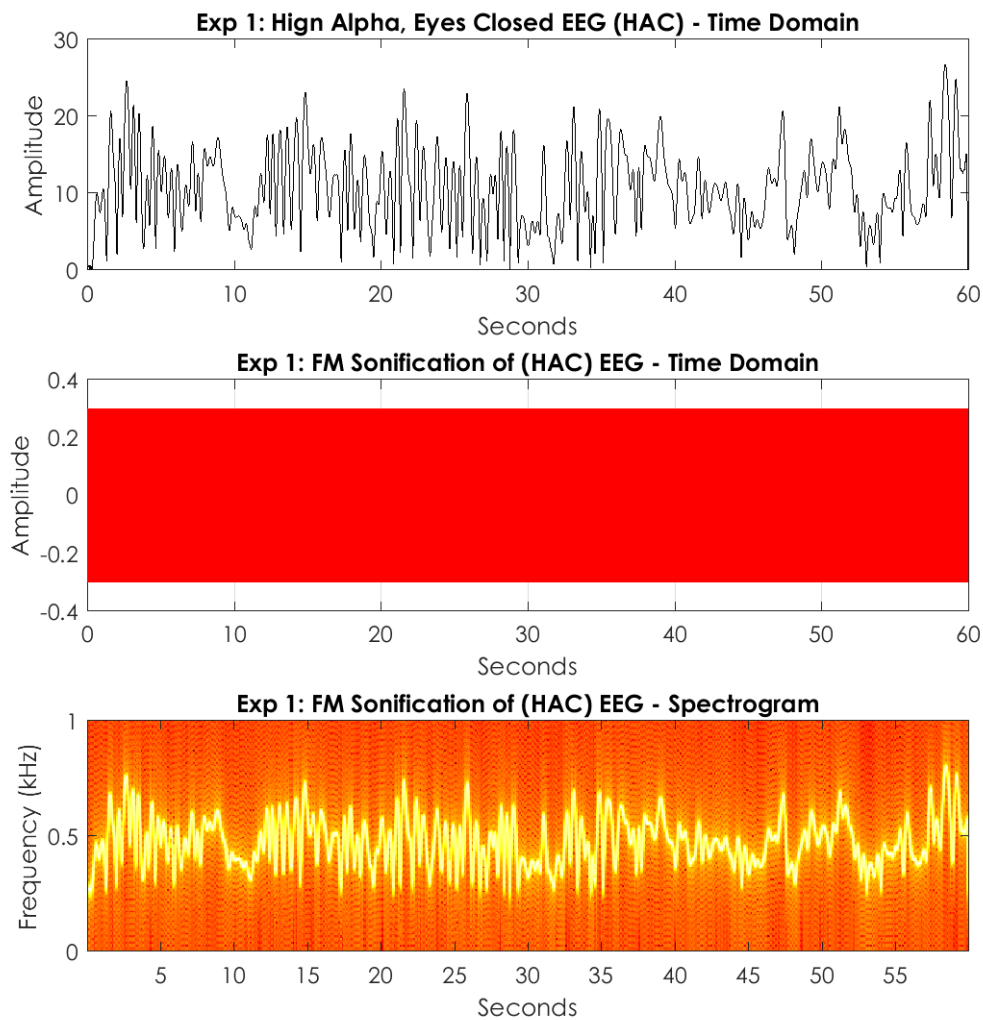
Thus the Pearson correlations for the EEG files with their sonifications at a zero time lag were computed. For the four AM sonifications the correlations were all 0.999 at  $p < 0.001$ . This demonstrates that the AM sonifications were all successfully sonified and no unexpected errors or distortions were introduced by the sonification process.

However, for the FM sonifications they were all 0.006 or less. This shows that the process of extracting the envelope of the FM sonification is meaningless for the FM sonifications. Therefore an alternative analysis method will be presented for the FM sonifications in the next section. .

#### 4.2.2.2. FM Sonification

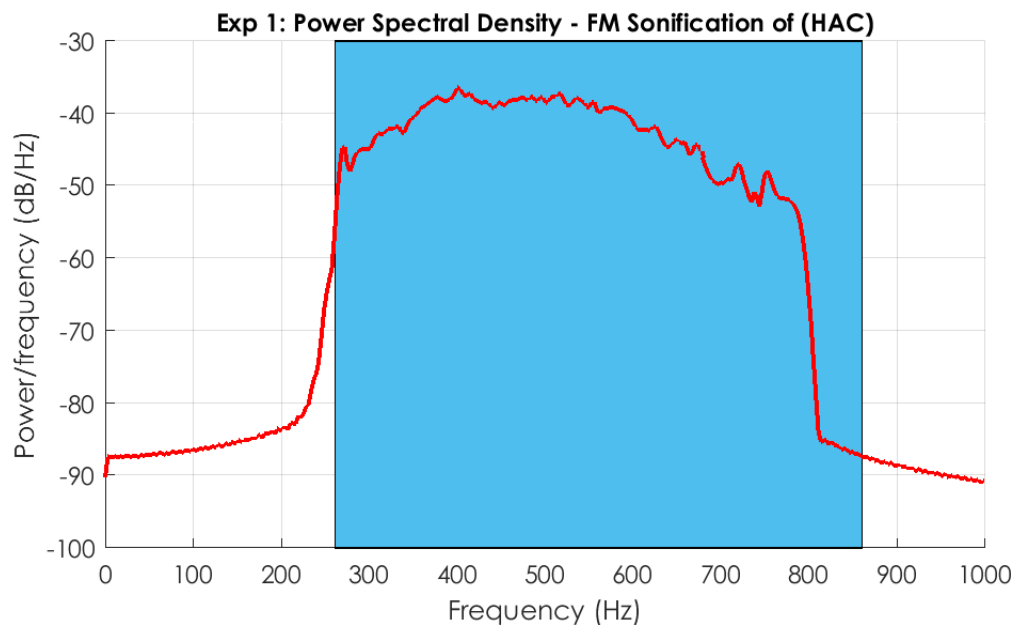
For FM sonification the EEG data was multiplied by a factor of 20 to give an output range of 0 to 600 and then each value was added to by either 261.6 or 523.2, giving an output frequency range of 261.6 to 861.6 Hz or from 523.2 to 1123.2 Hz. The output was then linearly interpolated to audio sample rate and saved as a .wav file.

**Figure 4.2.2.2.1**, shows the time domain plot of the high alpha with eyes closed EEG (HAC) in the top plot in blue. The middle plot is of the FM sonification and at this time resolution only the upper and lower 'envelope' can be seen and of course for an FM signal this is a flat line and in this case is from plus and minus 0.3. The bottom subplot shows the spectrogram, time frequency plot of the sound output of the same FM sonification.



**Figure 4.2.2.2.1:** Shows the original Alpha EEG (HAC) on the top subplot. The sound output from the FM sonification with the 261.6 Hz modulation frequency in the middle and the spectrogram of the same, on the bottom.

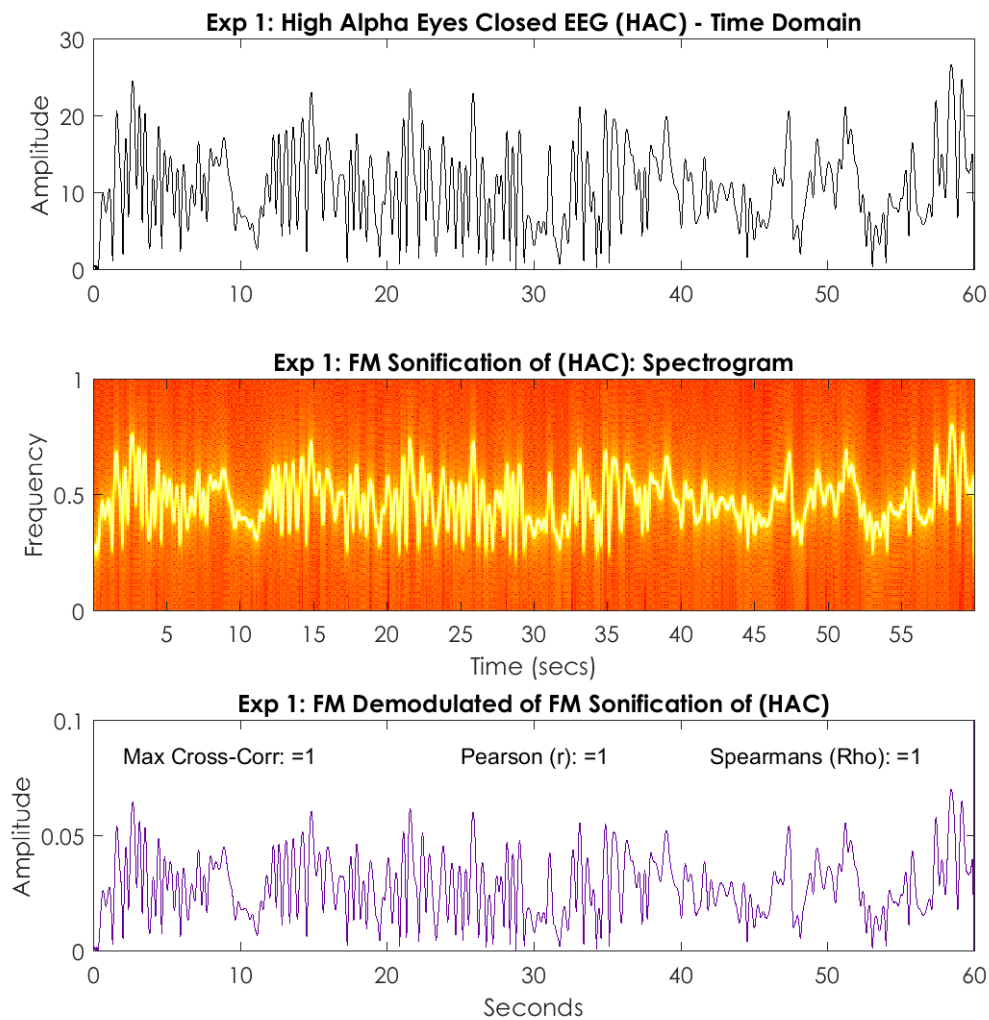
In **figure 4.2.2.2.2**, the frequency characteristics of the FM sonification with the 261.6 Hz modulation frequency show that the majority of activity was between 261.6 Hz and around 790 Hz.



**Figure 4.2.2.2:** Shows the Welch Power Spectral Density Estimate of the FM Sonification of HAC with the 261.6 Hz modulation frequency. The blue box shows, the maximum output frequency range of 261.6 to 861.6 Hz of the FM sonification.

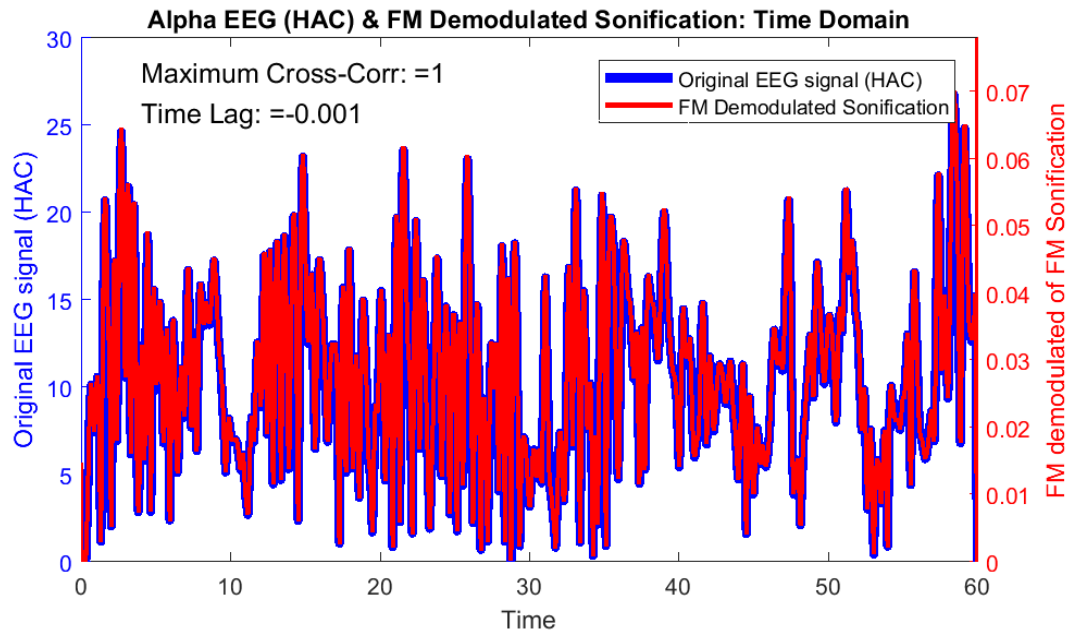
The yellow line in the spectrogram in [figure 4.2.2.1](#): shows the peak of activity for each time window (208 ms) in the sound file and the activity closely resembles the EEG activity. However, as discussed earlier when computing a correlation between the original EEG data and the amplitude envelope of the FM sonification this would create spurious results. Therefore it was necessary to demodulate the frequency information from the FM sonification using the function 'demod' in Matlab. `'Output = demod(SoundIn, 261.6, 48000, 'fm');'`

This function generates a time series vector of the same length as the original sound file that extracts the signal from frequency modulated data. In [figure 4.2.2.3](#), the bottom subplot, shows the FM demodulated signal in purple.



**Figure 4.2.2.2.3:** Shows the original EEG data in black in the top subplot, the spectrogram (short-time Fourier transform) of the FM sonification with the 261.6 Hz modulation frequency in the middle and the FM demodulated signal in purpal on the bottom.

Looking at **figure 4.2.2.2.3**, there is a clear similarity in the activity between all three subplots. Furthermore in **figure 4.2.2.4** the original EEG data was plotted in blue and the then FM demodulated signal was superimposed on top in red.



**Figure 4.2.2.2.4:** Shows the original EEG data in blue with the FM demodulated signal superimposed in red, (Because of the similarity between the two signals it was necessary to plot the original EEG data in a thicker line than the FM demodulated in order to see it).

Finally the original EEG data was correlated with the FM demodulated signal and again, the Pearson correlation at a time lag of zero for all four was 0.999 at  $p < 0.001$  for all of the four FM sonifications.

Therefore it can be concluded that both the AM and FM sonification techniques in experiment 1 show a perfect correlation with the original EEG data and that no errors or distortions were introduced by either sonification technique.

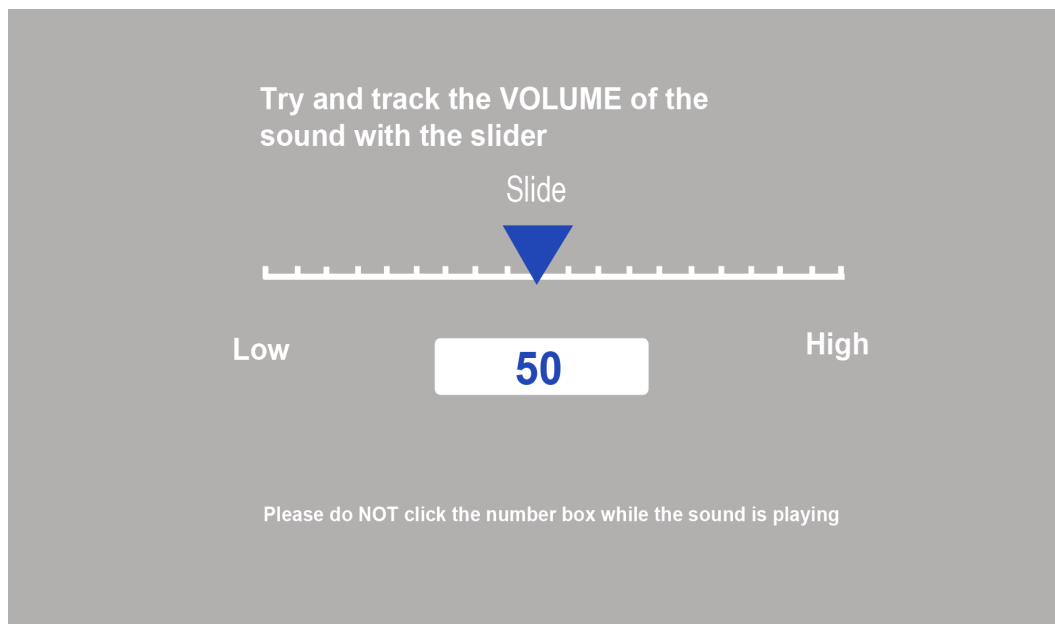
### 4.2.3. Experimental Procedure and Measures

Participants were seated in front of a laptop with Sennheiser HD 439 Headphones and played some example sounds to set the volume and

practice the tracking task. All stimuli and questionnaires were presented using PsychoPy (Peirce, 2007), an open source presentation software tool.

#### 4.2.4. Measure 1: Quantitative - Tracking

Participants were asked to track the activity of the sonification with a horizontal slider on the computer screen using the mouse. For the AM sonification, participants were instructed that they should move the slider to the right as the volume of the sound increased and to the left as it decreased. For the FM sonification the instruction was the same but for frequency.



**Figure 4.2.4:** Example of the Tracking Screen in PsychoPy for the AM sonification.

The goal of the tracking task is to test the whole data chain, from the data's transformation into sound, to the sound's conversion into perception and perception into a motor response of the participant. The testing session took between 15 and 25 minutes. 8 stimuli were used comprising of 2 (FM vs. AM) x 2

(eyes closed/eyes open) x 2 (Low Alpha vs. High Alpha) design. The presentation order was randomized across participants.

#### **4.2.5. Measure 2: Qualitative - Aesthetic**

After listening to each sound file the participants were asked to rate on a 20 point Likert-type scale both the arousal and valence (Schlosberg, 1954) of the sound (the screen was similar to the tracking screen seen in [figure 4.2.4](#)). The arousal question was "How exciting/energetic or passive/relaxing was the sound?" and the Valence question was "How positive/happy or negative/sad was the sound?" The left side of the slider was marked either "passive/relaxing" or "negative/sad" and scored 1 while the right side was marked "exciting/energetic" or "positive/happy" and scored 20.

#### **4.2.6. Measure 3: Qualitative - NASA-TLX**

Then participants were asked how easy or difficult they found the tracking task the NASA Task Load Index (NASA-TLX), which is a multidimensional workload questionnaire with six questions: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (Hart and Staveland, 1988). The questions were presented in a random order on each trial and the participant had to rate the questions with a slider similar to the one show in [Figure 4.2.4](#), with "low" on the left that scored 1 to "high" on the right with a score of 20, except for the 'performance' rating that ranged from "good" on the left to "poor" on the right.



#### **4.2.7. Measure 4: Qualitative - Metaphorical**

In a short post-experimental interview the participants were asked two questions: "Did these sounds remind you of any sound?" and "What do you think brainwaves would sound like if you could hear them?"

#### **4.2.8. Demographic Data & Musical Training**

Questions about age, gender and musical experience were left until the end of the study to minimize stereotype threat (Steele, 1997) which is the participant perception of the researcher's expectation. This has been shown to affect performance. The four questions to assess the musical experience were: M1) "I engaged in regular, daily practice of a musical instrument (including voice i.e. singing) for "X" or more years", M2) "At the peak of my interest, I practiced "X" or more hours per day on my primary instrument", M3) "I have had "X" or more years of formal training on a musical instrument (including voice) during my lifetime", and M4) "I have had formal training in music theory for "X" or more years".

### **4.3. Results**

The Alpha level was fixed at 0.05 for all statistical tests. Greenhouse-Geisser correction was used to correct for unequal variances. For multivariate analysis, Wilks' Lambda L was used as the multivariate criterion. All variables were normally distributed according to the Kolmogorov-Smirnov test. As there were no significant differences between low and high frequency alpha sonifications for any measure, they were combined for subsequent analysis.

#### **4.3.1. Participant Data**

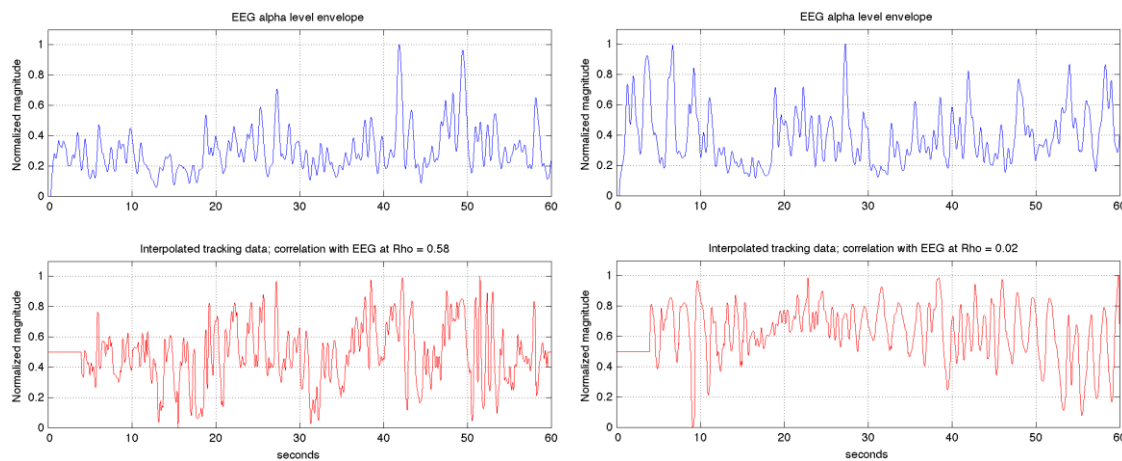
Seventeen participants, mean age 45.65 (SD = 13.09), 8 females, took part in the experiment. All had a normal level of vision, hearing and cognitive functioning and were over 18 years old. The participants signed a consent form, were not paid or given any inducements to participate and were informed they had the right to withdraw at any time and their data would be destroyed. The experiment received ethics approval from the Open University Human Research Ethics Committee number HREC/2014/1733/Steffert and was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2000).

#### **4.3.2. Tracking Accuracy and Pre-Processing**

Tracking accuracy was computed by correlating the original EEG data that generated the sonification with the participants' slider response to the sound output of the sonification.

First, the tracking data points (from each time the slider changed the position) was interpolated using cubic spline data interpolation in Matlab, to match the time scale and sampling rate (500Hz) of the EEG data. EEG data was also pre-processed by extracting the amplitude envelope using a Hilbert transform, and then using a moving average window of 200 sample length (0.4 s). To compensate for differences in the participant's reaction time and therefore variations in the lag of the tracking data, an iterative process to compute the correlation coefficient for all delays of up to 1 second to find the maximum was implemented in Matlab. The best match was also visually inspected to minimise

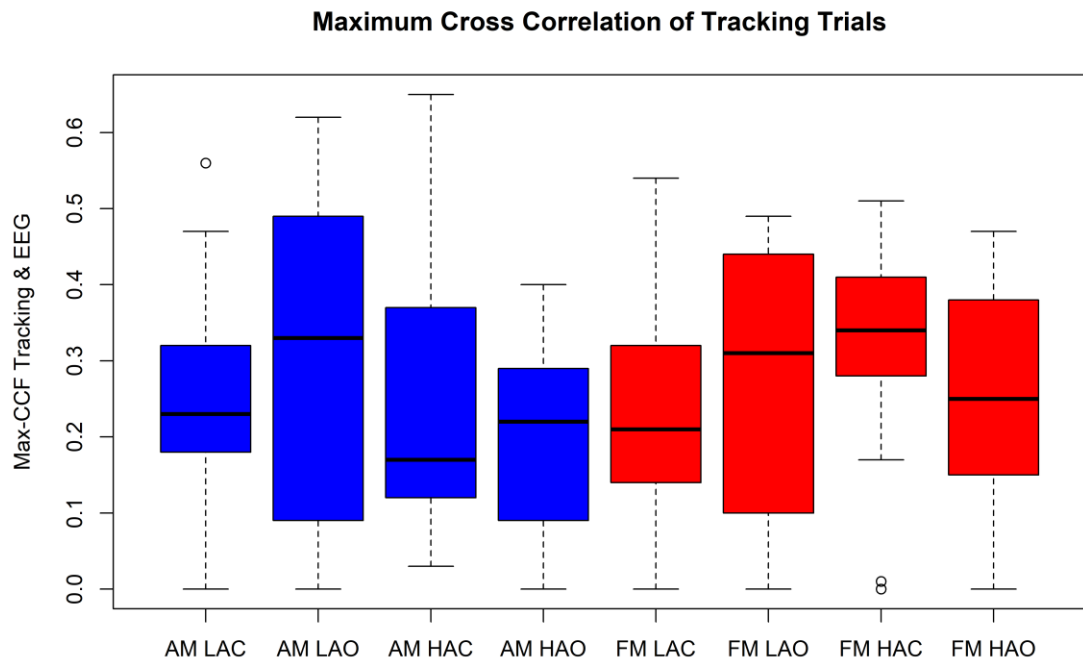
the risk of erroneous matches. **Figure 4.3.2.1** shows the EEG data in blue and a good and bad example of tracking in red.



**Figure 4.3.2.1:** EEG alpha level envelopes (in blue) that were used for sonification and corresponding interpolated tracking data (in Red). Left panel – good tracking example ( $Rho = 0.58$ ), Right panel – bad tracking example ( $Rho = 0.02$ ). First 4 s of tracking data are replaced by constant value since this data was changed by the spline function.

The mean “tracking accuracy” i.e. the Pearson correlation coefficient  $Rho$  between the EEG data and the tracking data ranged between 0 and 0.58 ( $SD = 0.2$ ). For seven participants the max correlation coefficient for all 8 conditions was lower than 0.4. As this is somewhat low, this suggests that some of the participants could either not hear the signal in the sonification, or could not move the slider very accurately to track the data, or both. **Figure 4.3.2.2**, shows the tracking accuracy data for all participants in the 8 trials in a Box-&-whisker Plot, the blue bars are the FM trials and the red the AM. Nearly all the trials have scores close to zero and the trials with the highest two scores: ‘AM with High

frequency sonification with Eyes Open' (AMHAO) and 'AM with Low frequency with Eyes Open' (AMLAO) with scores of over 0.5 shows a large spread of scores.



**Figure 4.3.2.2:** Shows a Box-&-Whisker plot of the median and quartiles of the Cross Correlation of the tracking data with the EEG data for all 17 participants for the 8 tracking trials. Blue is AM and Red is FM trials. (The open circles are outliers, i.e. 1.5 times smaller or larger than the interquartile range from the first or third quartile)

Because there were four trials for each of the two sonification techniques, the tracking accuracy scores of each trial can be correlated with all the other trials to make the Correlations Matrix in [Table 4.3.2.1](#).

	FMHAO	FMHAC	FMLAO	FMLAC	AMHAO	AMHAC	AMLAO	AMLAC
FMHAO	1	0.495	0.324	0.285	0.410	-0.014	0.098	0.058
FMHAC	0.495	1	0.308	0.515	0.633	0.113	0.353	0.627
FMLAO	0.324	0.308	1	0.154	0.461	-0.533	0.228	-0.154
FMLAC	0.285	0.515	0.154	1	0.340	-0.078	0.343	0.279
AMHAO	0.410	0.633	0.461	0.340	1	-0.132	0.454	0.198
AMHAC	-0.014	0.113	-0.533	-0.078	-0.132	1	-0.114	0.435
AMLAO	0.098	0.353	0.228	0.343	0.454	-0.114	1	0.453
AMLAC	0.058	0.627	-0.154	0.279	0.198	0.435	0.453	1
	<b>0.368</b>	<b>0.439</b>	<b>0.262</b>	<b>0.318</b>	<b>0.173</b>	<b>0.063</b>	<b>0.264</b>	<b>0.362</b>

**Table 4.3.2.1:** Shows the Pearson Correlations Matrix of each trial with the others. The bottom row is the mean correlations for each trial with the other three trials of the same sonification technique. E.g. the first column shows a mean of 0.368 for the correlation of FMHAO with FMHAC, FMLAO and FMLAC.

The **FM** trials have a mean cross correlation of **0.347** with the other FM trials and the maximum was **0.515** and minimum was **0.154**. For the **AM** tracking trials the mean cross correlation was **0.234** with the other AM trials and the maximum was **0.454** and minimum was **-0.132**.

This Correlations Matrix can be seen as a proxy “Test Re-test” reliability measure and suggests this test has a low reliability, although it should be noted this is not a genuine test-retest reliability measure, because the correlations were with similar but not identical data and the repetitions were in the same session, there for the differences in trials could be due to differences in the eyes open vs. eyes closed EEG or in the perception of high vs. low frequency sonification.

### 4.3.3. The difference between AM and FM sonifications

A two-way within-subjects MANOVA was conducted using the 6 questions from NASA-TLX, subjective emotional ratings of valence and arousal (VAL and ARO),

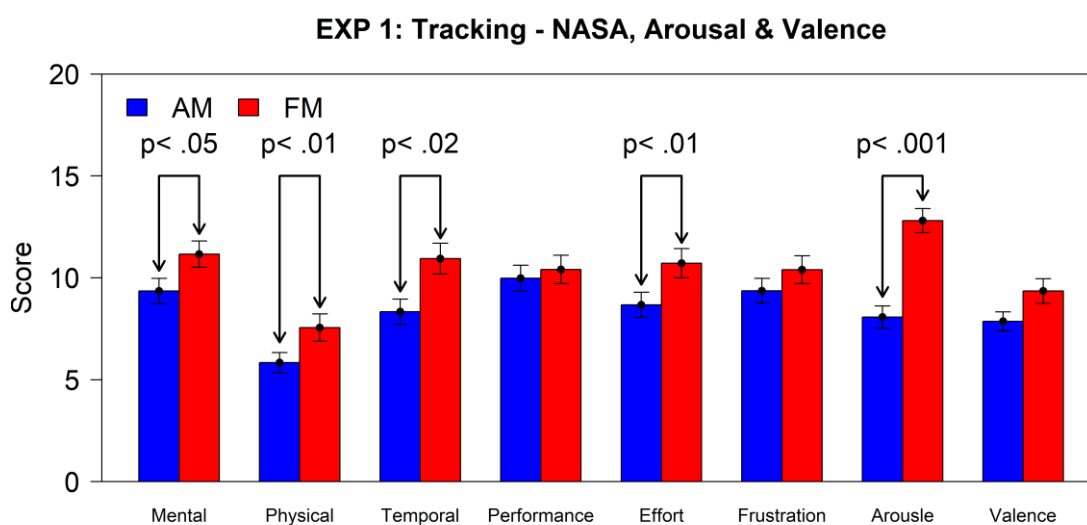
and 'Tracking accuracy' correlation coefficient Rho. The design was sonification type (FM/AM) x EEG condition (eyes closed/eyes open).

Four questions regarding musical experience were used for creating 2 types of subgroups. The first type was based on answers from M1 and M2 questions and forming subgroups with (10 out of 17 participants) and without musical instrument experience. The second type was based on answers from M3 and M4 questions and forming subgroups with (10 out of 17 participants) and without formal musical education. The two resulting groupings regarding musical experience differed slightly from each other (by 4 people).

The overall multivariate effect of sonification type was significant, with the difference between AM and FM at Wilks' Lambda = 0.108,  $F(9, 8) = 7.34$ ,  $p < 0.005$ ,  $\eta^2 = 0.892$  (Eta-squared). Univariate tests showed significance of this modulation type effect for a number of measures. For the **Mental Demand** scale, difference was at  $F(1, 16) = 7.05$ ,  $p < 0.05$ ,  $\eta^2 = 0.306$ , showing that FM was reported as having higher mental demand than AM-based sonification, ( $M = 11.2$   $SD = 1.2$ ) vs. ( $M = 9.4$   $SD = 1.1$ ). For the **Physical Demand** scale the significance was at  $F(1, 16) = 8.66$ ,  $p < 0.01$ ,  $\eta^2 = 0.351$ , with FM being reported as requiring more physical activity ( $M = 7.6$ ,  $SD = 1.2$ ) than AM-based sonification ( $M = 5.8$ ,  $SD = 0.8$ ). For the **Temporal Demand** scale the significance was at  $F(1, 16) = 7.45$ ,  $p < 0.05$ ,  $\eta^2 = 0.318$ , with FM-based sonification being rated as having more time pressure ( $M = 10.9$ ,  $SD = 1.4$ ) than for AM-based ( $M = 8.3$ ,  $SD = 1.0$ ). For the **Effort scale** the difference was significant at  $F(1, 16) = 9.3$ ,  $p < 0.01$ ,  $\eta^2 = 0.368$  with FM requiring greater effort ( $M = 10.7$ ,  $SD = 1.3$ ) than AM-based sonification ( $M = 8.7$ ,  $SD = 1.2$ ). On the subjective **arousal scale**, FM-based sonification was significantly more exiting/energetic ( $M = 12.8$ ,  $SD = 1.1$ )

than AM-based one ( $M = 8.1$ ,  $SD = 0.8$ ) with  $F(1, 16) = 24.49$ ,  $p < 0.001$ ,  $\eta^2 = 0.605$ . Finally, for the tracking accuracy the **Rho values** were significantly higher for FM-based ( $M = 0.21$ ,  $SD = 0.34$ ) than for AM-based sonification ( $M = 0.13$ ,  $SD = 0.36$ ) at  $F(1, 16) = 9.92$ ,  $p < 0.01$ ,  $\eta^2 = 0.383$ . (See [Table 4.3.3.1](#))

On a few other scales, differences between two sonifications could be observed, but they did not reach significance. For the **valence scale**, the difference between FM and AM sonification was  $F(1, 16) = 3.18$ ,  $p = 0.1$ ,  $\eta^2 = 0.166$  with FM being judged more positive/happy ( $M = 9.4$ ,  $SD = 1.0$ ) than AM ( $M = 7.9$ ,  $SD = .7$ ). **Frustration** was higher for FM ( $M = 10.4$ ,  $SD = 1.1$ ) than for AM ( $M = 9.36$ ,  $SD = 1.0$ ) but did not reach significance  $F(1, 16) = 2.42$ ,  $p = 0.14$ ,  $\eta^2 = 0.131$ . Interestingly, despite FM being rated higher than AM on all the other measures, the self-rating of **Performance** showed no difference between the two sonification methods. The difference was at  $F(1, 16) = 0.302$ ,  $p = 0.59$ ,  $\eta^2 = 0.019$ , with FM ( $M = 10.41$ ,  $SD = 1.2$ ) and AM ( $M = 9.96$ ,  $SD = 1.1$ ) on a scale of 1 to 20.



**Figure 4.3.3.1:** Shows the mean and standard error of the subjective ratings on a 20 point Likert type scale ranging from 1 to 20 for the six questions of the NASA-

TLX: Mental Demand (Men), Physical Demand (Phy), Temporal Demand (Tem), Performance (Per), Effort (Eff), Frustration (Fru), as well for Arousal (Aro) and Valence (Val), with the *p*-values for the statistically significant differences between AM in (blue) and FM (red).

Within Subjects Effect		Value	F	Hypothesis is df	Error df	Sig.	Partial Eta <sup>2</sup>
<b>Mod</b>	Wilks' Lambda	0.108	7.344 <sup>c</sup>	9	8	<b>0.005</b>	0.892

	Greenhouse Geisser	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta <sup>2</sup>
<b>Mod</b>	Mental	111.243	1	111.243	7.045	<b>0.017</b>	0.306
	Physical	100.654	1	100.654	8.66	<b>0.010</b>	0.351
	Temporal	230.36	1	230.36	7.45	<b>0.015</b>	0.318
	Performance	6.184	1	6.184	0.302	0.590	0.019
	Effort	142.066	1	142.066	9.304	<b>0.008</b>	0.368
	Frustration	36.029	1	36.029	2.415	0.140	0.131
	Arousal	762.382	1	762.382	24.488	<b>0</b>	0.605
	Valence	75.007	1	75.007	3.182	<b>0.093</b>	0.166
	R Tracing Ac	0.214	1	0.214	9.919	<b>0.006</b>	0.383

Measure	mod	95% Confidence Interval			
		Mean	Std. Error	Lower Bound	Upper Bound
<b>Mental Demand</b>	FM	11.162	1.242	8.529	13.795
	AM	9.353	1.057	7.113	11.593
<b>Physical Demand</b>	FM	7.559	1.229	4.954	10.164
	AM	5.838	0.845	4.047	7.63
<b>Temporal Demand</b>	FM	10.941	1.375	8.027	13.856
	AM	8.338	1.048	6.117	10.559
<b>Performance</b>	FM	10.412	1.281	7.696	13.127
	AM	9.985	1.119	7.614	12.357
<b>Effort</b>	FM	10.721	1.292	7.981	13.46
	AM	8.676	1.147	6.246	11.107
<b>Frustration</b>	FM	10.397	1.131	8.000	12.795
	AM	9.368	1.015	7.217	11.519
<b>Arousal</b>	FM	12.809	1.095	10.488	15.13
	AM	8.074	0.804	6.368	9.779
<b>Valence</b>	FM	9.353	1.05	7.126	11.58
	AM	7.868	0.713	6.356	9.379
<b>R - Tracing Accuracy</b>	FM	0.214	0.034	0.142	0.286
	AM	0.134	0.036	0.057	0.211

**Table 4.3.3.1:** Show the means, confidence and F scores of the NASA-TLX ratings.



Although the tracking accuracy was significantly lower than in earlier pilot testing, and nearly all participants reported difficulties in moving the slider fast enough to keep up with the sound, the combination of continuous tracking data and subjective work load assessments of the tracking task has provided some interesting insights, as will now be summarised.

Overall the 17 participants performed better on tracking the FM sonification than the AM, but did not feel their performance was any better. They found tracking of FM sonification more mentally, physically and temporally demanding and more effortful but did not feel any difference in frustration between the two sonifications.

This could be interpreted as indicating that the participants could hear the data more accurately with the FM sonification therefore performed the tracking task more accurately and as a consequence of hearing more information, found the task more demanding. In other words, those who did not perceive the modulation may have found the task "easy" because they were unaware they were missing data and therefore found the task less demanding.

This interpretation seems to agree with some previous non-EEG sonification studies (Flowers, 2005) (see [chapter 2.3.7](#)) suggesting that FM sonification is generally better than AM sonification for presenting data.

#### **4.3.4. The effect of the EEG condition**

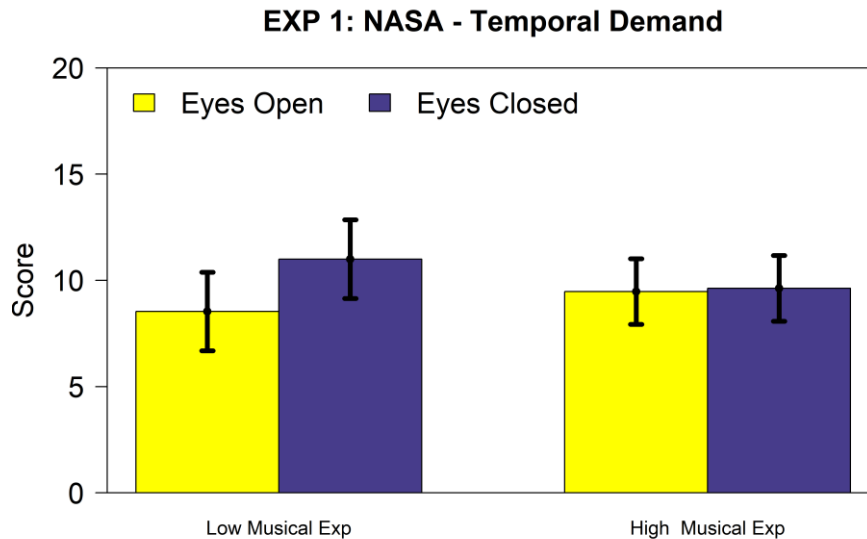
Participants rated the sonifications of EEG from eyes closed condition as having a higher Frustration ( $M = 10.75$ ,  $SD = 1.1$ ) than the eyes open condition ( $M = 9.02$ ,  $SD = 1.0$ ) with a statistical significance  $F(1, 16) = 6.15$ ,  $p = 0.025$ ,  $\eta^2 = 0.278$ ,

regardless of sonification type or frequency band. This may be because there is more alpha activity in the eyes closed condition with more variability. No interaction between EEG and sonification type reached significance.

#### 4.3.5. Musical experience

Ten out of 17 participants had musical experience either in the form of playing an instrument or some formal training, music theory training and practiced at least 30 minutes a day at some time in their life. Two grouping factors were created and a repeated two-way within-subject MANOVA with additional grouping factor of either musical instrument experience, or musical education was computed.

No significant effect for the musical education factor was found. However, two significant interactions between musical instrument experience and stimuli type could be seen. First, sonification type interacted with subgroups factor for the arousal ratings at  $F(1, 16) = 5.33$ ,  $p = 0.036$ ,  $\eta^2 = 0.262$ . Those who played a musical instrument judged FM sonification a lot more arousing ( $M = 14.13$ ,  $SD = 1.4$ ) than those that did not ( $M = 10.93$ ,  $SD = 1.7$ ), but there was less difference between subgroups in the arousal ratings to the AM sonification (8.5 vs. 7.8). A second significant interaction could be seen between the subgroups and EEG condition at  $F(1, 16) = 5.59$ ,  $p = 0.032$ ,  $\eta^2 = 0.272$ . The participants that did not play a musical instrument found that the sonification of EEG from the eyes closed condition ( $M = 11.00$ ,  $SD = 1.9$ ) was more temporally demanding to track, than the eyes open condition ( $M = 8.54$ ,  $SD = 1.8$ ). No such difference was found for listeners with music experience.



**Figure 4.3.5:** Interaction between temporal demand factor from NASA-TLX and subgroups of musical experience level (playing any musical instrument (N. 10) or not (N.7)). The eyes open and close legend stands for sonification of EEG data from open or closed eyes condition.

#### 4.3.6. Post-experimental interviews

To the question “Did these sounds remind you of any sound?” Only one person said “No” and the most frequent answer with 6 (27 %) said “wind”. Two people thought the sonifications sounded like “The Clangers” from the UK Children’s TV show and most of the other answers shared a similar theme - replies included; “police siren” “vacuum cleaner machine”, “whistle”, “trombone”, “oscilloscope”, “AV meter” and “happy complaining ghosts”. Some people did not like the sounds at all and said it reminded them of “horror movies” or sounded like a “cheese grater”.

For the question “What do you think brain waves would sound like if you could hear them?” Two people did not answer, three said “wind” (16%) and two

thought the sonification did sound like brainwaves (11%) and 8 (42%) of the responses had a theme of busy activity like “boiling water”, “busy like a switch board”, “a terrible roaring noise” and “noise, white noise”. One person said “music” and another “like a cheese grater”.

#### **4.4. Discussion**

This present experiment can be seen as an initial step in the development of a methodology to compare the effectiveness of real-time EEG sonifications. The main finding of the listening tests of 17 participants was that, despite the tracking of FM sonification being rated as more mentally, physically and temporally demanding and more effortful, the continuous tracking accuracy was significantly more accurate than for AM. Nearly 90% of the variability in combined measures comparison (MANOVA) can be explained by the type of sonification (i.e. FM or AM). Importantly, without a quantitative behavioural measure of a person’s ability to perceive the data changes, the results of subjective evaluation would lead to the false conclusion that the AM sonification was a better method as it was rated as easier to track.

Only a few participants liked the wailing sounds of the AM and FM sonifications and some vehemently disliked them. Three participants came close to terminating their involvement in the experiment. Despite the conceptual simplicity of the sounds, many participants either thought the sonifications sounded like brain waves or had some similarities to what they expected brain waves to sound like.

This experiment used pre-recorded EEG fragments that captured a range of different alpha activity patterns that exemplified the typical activity of eyes closed and eyes open conditions. However, there was only one statistically significant difference between sonifications of EEG from eyes closed and eyes open condition: participants rated data from eyes closed condition more frustrating to track. Interestingly, when adding musical experience as a subgroup variable, it revealed that listeners who do not play any musical instrument found EEG sonification of the eyes closed data significantly more temporally demanding to track as compared to their own ratings of eyes open sonification, and to the ratings from users with musical experience. But it should be remembered that the 6 questions from the NASA-TLX were about the workload of the tracking task and only the arousal and valence ratings were about the quality of the sound of the sonifications.

This highlights a distinctive feature of this experiment, which used continuous real-time tracking to measure the difference in trackability between two types of sonification, without using sonification to identify or sort the data. The experiment also contrasts with those that solely measure subjective preferences for sonifications. As previously noted, there are a few EEG sonification studies that use the 'two-alternative forced-choice method' and some identify the onset of a particular activity. But one of the shortcomings of such methodologies is their inability to assess the temporal dynamics of the data and its perception.

#### **4.4.1. Reflection in the light of related research**

The field of psychoacoustics has been researching sound and music perception for over one hundred and fifty years, so methodologies from this domain may

help to illuminate the present study. However one of the problems with many psychoacoustic studies is that they tend to use very short sound clips that may not capture the temporal dynamics of a typical sonification listening session. So, for example, the International Affective Digitized Sounds (IADS) (Stevenson and James, 2008), which has created a normative emotional stimuli database, uses sounds of only 6-seconds in duration.

On the other hand, administering a questionnaire at the end of a 1 to 5-minute listening epoch will also fail to capture the temporal dynamic nature of most sound/music. Madsen (1997) argues that what is needed is a “continuous non-verbal measurement of a participant's response to the music/sound stimuli that can expose the dynamic contours of a listening experience without distracting the participant from the listening task”. To this end, Madsen and colleagues at the Center for Music Research at Florida State University have developed and validated with a large number of studies a ‘Continuous Response Digital Interface’ (Madsen, 1990) that allows the user to turn a dial in real-time to log their immediate and continuous response on a continuum between two extremes such as “Positive” to “Negative” or “Lively” to “Passive”. This current experiment could be seen as a variant of the Madsen methodology but within the sonification domain.

#### **4.4.2. Final reflection on experiment 1**

The objective of this research was to develop a sonification validation method that is specifically suited to the nature of real-time EEG feedback as opposed to time series data in general.

Whilst the continuous tracking of a sound stream with a mouse is a poor proxy for the perceptual decoding of a continuous signal, any lag from the motor response will apply equally to all conditions, and this experiment has shown that such an approach can generate a quantitative assessment of the real-time trackability of a sonification. Furthermore, although some of the older users without computer experience had difficulties tracking, and despite considerable variability in tracking accuracy between participants, the combination of quantitative and qualitative data helped to illuminate the relative usefulness of each sonification method.

In the next chapter, the key step will be to test the use of real-time sonification of the participant's own EEG rather than using pre-recorded EEG. Furthermore the same two sonifications will be used in order to make a comparison between the performance of sonifications in a real-time neurofeedback task and the tracking task.

## Chapter 5: Experiment 2

### Real-Time Left frontal Alpha EEG Sonification Neurofeedback.

#### 5.1. Introduction

Experiment 1 measured participants' ability to perceive and physically track in real-time the rapid and complex activity of a *pre-recorded* EEG signal, sonified in two different ways (AM vs. FM). A battery of both quantitative and qualitative assessment tools was used to compare the sonifications.

The subject of this chapter, the second experiment, used the same two sonifications, but this time applied to a real neurofeedback task using participants' own live EEG. The neurofeedback task, described in detail below, was designed to improve mood (though this was not known to participants). Consequently two new quantitative comparisons between sonifications became possible and were carried out. Firstly, the extent to which participants' moods actually changed; and secondly any measured changes in the relevant aspects of their EEG.

More specifically, in this second experiment, the participant's alpha activity was mapped onto the volume (or frequency) of the AM and FM sonifications respectively. Participants were asked to try to reduce the volume of the AM sonification or to lower the frequency of the FM sonification, so decreasing their alpha power. A single session of single-channel real-time neurofeedback was used for this experiment.

As explained in [section 2.1.10](#) a reduction in left frontal Alpha activity is associated with a reduction in tension and avoidance behaviour. So, as



indicated above, a questionnaire measuring emotion was used to see if there was any change in mood measures pre and post the training. The same NASA task load index used in the previous experiment was also used to measure any subjectively rated quantitative differences between the two sonification techniques.

The experimental research questions were:

**EQ5.1)** Can people reduce their left frontal alpha EEG levels, with the aid of real-time EEG sonification neurofeedback?

**EQ5.2)** Will there be a concomitant decrease in avoidance type behaviour with any reduction in participants left frontal alpha EEG levels?

**EQ5.3)** Will there be a difference in outcome measures between the two different sonification techniques?

**EQ5.4)** Are the outcome measures of experiment 2 predicted by the tracking scores in experiment 1?

The main goals of this second experiment were to test if people could modify their own alpha activity with the use of EEG sonification and to check if there was a differential learning outcome between the two sonifications using a combination of quantitative and qualitative measures and to see if there is any replication of the FM effectiveness detected in Experiment 1.

The outcome of this experiment did not show a significant change in alpha EEG activity across the training trials;

However the subjective emotional rating scale did show a significant change in the predicted direction with the FM sonification neurofeedback training but not the AM.

Furthermore this second experiment replicated the workload findings seen in the first experiment.

## **5.2. Experiment Design**

### **5.2.1. Frontal Alpha EEG**

In this second experiment, unlike in Experiment 1, the aim was to measure the extent to which participants could use the real-time sonification of their EEG to modify their own brain activity. Consequently it was necessary to choose a specific aspect of the EEG signal to be sonified, and which participants could benignly attempt to self-modify. Therefore brain activities associated with positive emotions were chosen.

As discussed in [chapter 2.1.10](#), Davidson (Davidson et al., 1999) suggests that greater activation of the left frontal cortex of the brain, in comparison to the right, is associated with more positive emotions. By contrast, greater activation of the right frontal cortex is associated with more negative emotions. A useful way to quantify the level of activation of these areas is to measure EEG Alpha waves in the range from 8 to 12 Hz. This frequency band is inversely associated with oxygen and glucose consumption, the fuel for the brain (Cook et al., 1998); (See section 2.1.6. EEG and Brain Blood Oxygen, page 50) therefore as the alpha activity increases, this indicates that brain activity is decreasing. Thus,

right vs. left relative frontal EEG Alpha asymmetry can be a useful index of right vs. left frontal cortical activity and, in turn, an indicator of positive vs. negative emotion (Davidson, 2004a).

However, it was felt that because historically the majority of EEG research in this field has looked at averaged data over seconds and minutes, not enough is known about the temporal dynamics of frontal alpha asymmetry when computed from two electrodes in real-time. Therefore to be compatible with Experiment 1 the EEG alpha activity from the left forehead was sonified as a proxy measure of frontal alpha asymmetry and participants were instructed to try and lower the amplitude of the AM sonification or to lower the frequency of the FM sonification. Unbeknownst to participants, this corresponded to lowering the alpha, thereby, in broad terms, increasing positive emotions and decreasing negative emotions or avoidance behaviour.

At the outset of this experiment, it was not anticipated that participants would necessarily learn to change their own EEG activity in a single session of two different 9 minute training trials. However, it was important to measure the effects of any differences between the two sonifications as sensitively as possible, using a within subject design, with two different sonifications in the same session and a variety of measures. In particular, as will be presented in [section 5.4.5.1](#) below, for the purposes of this experiment, it was necessary to create a questionnaire with greater precision and suitability for measuring emotional response, than the relatively simple two-item questionnaire of Experiment 1 (see [section 4.3.5](#)).

### 5.3. Methods

#### 5.3.1. Real-time EEG system

For this second experiment a commercially available consumer grade EEG monitoring device was chosen. The Muse brain-sensing headband ([Figure 5.3.1](#)) is a simple non-invasive 4-channel wireless EEG headset produced by InteraXon (InteraXon Inc.). The headset has seven dry sensors that go on the skin; two on the left and right of the forehead (AF7 and AF8), two behind the ears worn like spectacle frames, and three reference sensors in the middle of the forehead. The Muse is a low cost consumer device that can record and display real-time EEG with minimal preparation. Muse has online artifact detection of eye blinks, muscle tension (Thompson, Steffert, Ros, et al., 2008) or bad connections and freezes the signal when these are detected. The Muse can sample the EEG at 220 Hz or 500 Hz and can output the raw EEG, or filtered frequency bands at 10Hz, as well as providing three channels of accelerometer.



**Figure 5.3.1:** Muse EEG Headset from InteraXon Inc. This is a 4 channel dry electrode consumer grade Bluetooth EEG system.

### 5.3.2. Sonifications of the Electroencephalogram

The free Muse software development kit (SDK), captures the Bluetooth data from the headset and uses a 'Windows PowerShell' Script to send the open sound control (OSC) data over 'User Datagram Protocol' (UDP) 'localhost'. to any compatible software. OSC is a networking protocol that originated in sound and music computing.

In Muse-io the 'Preset 14' was selected, which outputs the EEG data at a sampling rate of 220 Hz at a bit depth of 10, with a Notch filter of 45 to 65 Hz inclusive. The PowerShell Script was:

```
"muse-io --device-search Muse-354B --osc osc.udp://localhost:5000 --preset 14 -  
-50hz"
```

The Muse calculates the relative band powers by dividing the absolute linear-scale power of a band by the sum of the absolute linear-scale powers in all bands and gives a value range from 0 to 1. The band powers are then averaged over 100 ms to return a value 10 times a second and sent to Pure Data (Puckette, 2002).

In Pure Data the Audio sample rate was set to 48,000 Hz and the relative alpha band (7.5 to 13 Hz) power from the left frontal electrode (AF7) of the Muse headset was then sonified in real-time and the EEG data and sound files were saved to disk.

The sonification techniques used were similar to those used in Experiment 1 (See [section 4.2.2](#)); however as no difference between the two carrier frequencies

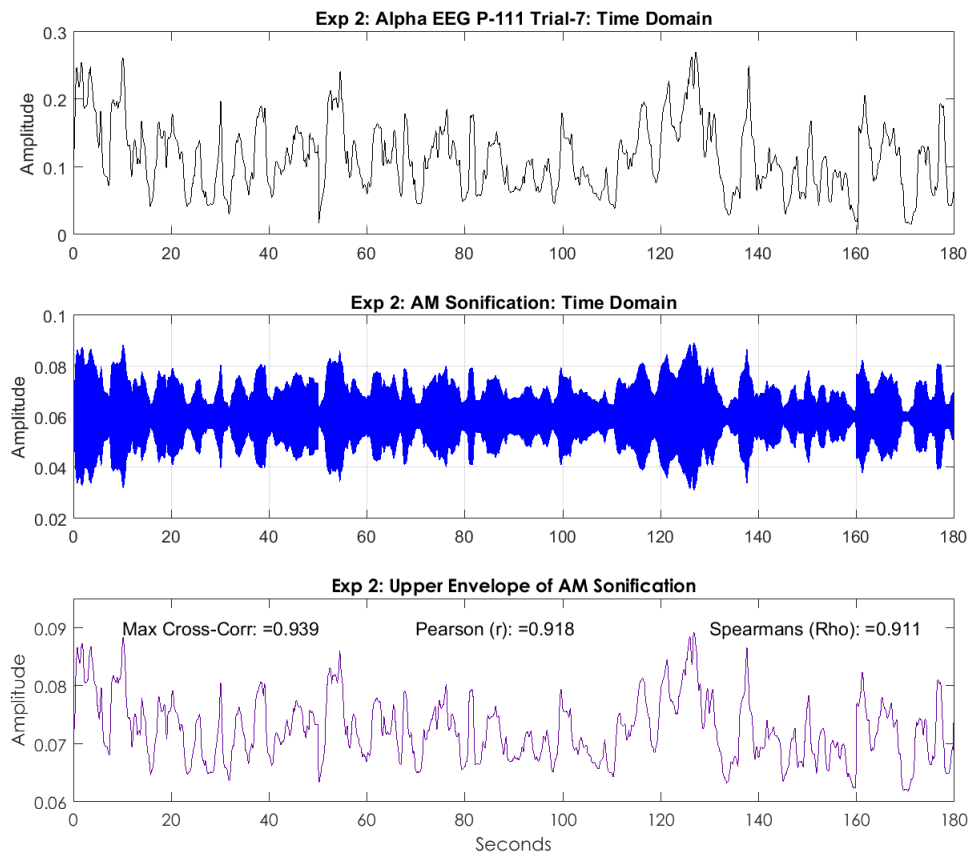


**Figure 5.3.2.1:** Shows the Pure Data patch used in experiment 2 for the real-time sonification of the EEG.

The Alpha EEG is received as an OSC message and the 'Horseshoe' section in light blue, shows if there is a bad signal. The two light blue vertical sliders display the real-time Alpha power for AF7 (left) and AF8 (right). The grey section labelled 'AM\_AF7' computes the AM sonification and the grey box labelled 'FM\_AF7\_261.6' generates the FM sonification. The 'Timer' in the turquoise box, runs each trial for 180 seconds and the 'File Name' in grey generates the unique filename that is used to save the files.

The 'Sound Output' in the purple box, controls the output volume, the 'Record Sound' records the sound output and the 'Save\_AF7\_Alpha' saves the EEG data.

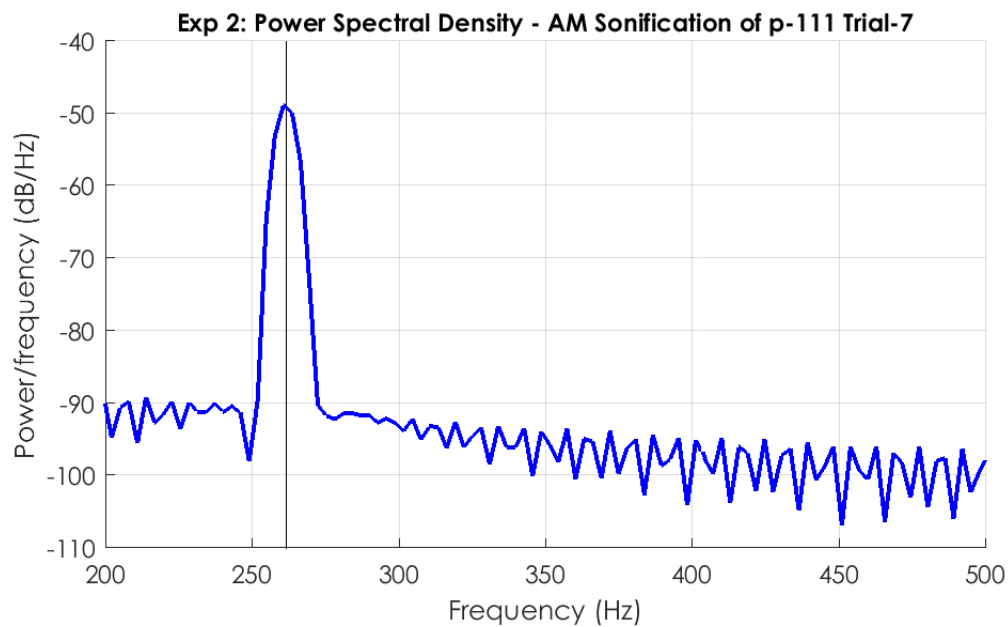
The following section will evaluate the sonifications output from this Pure Data patch. **Figure 5.3.2.2**, shows the Alpha EEG and the output of the AM sonification from participant 111 during a training trial, where they were trying to reduce their alpha activity by lowering the volume of the AM sonification.



**Figure 5.3.2.2:** Shows the original Alpha EEG from participant 111, on the top. The sound output from the AM sonification with the 261.6 Hz modulation frequency in the middle and the upper envelope of the sound, extracted using Hilbert transform, on the bottom.

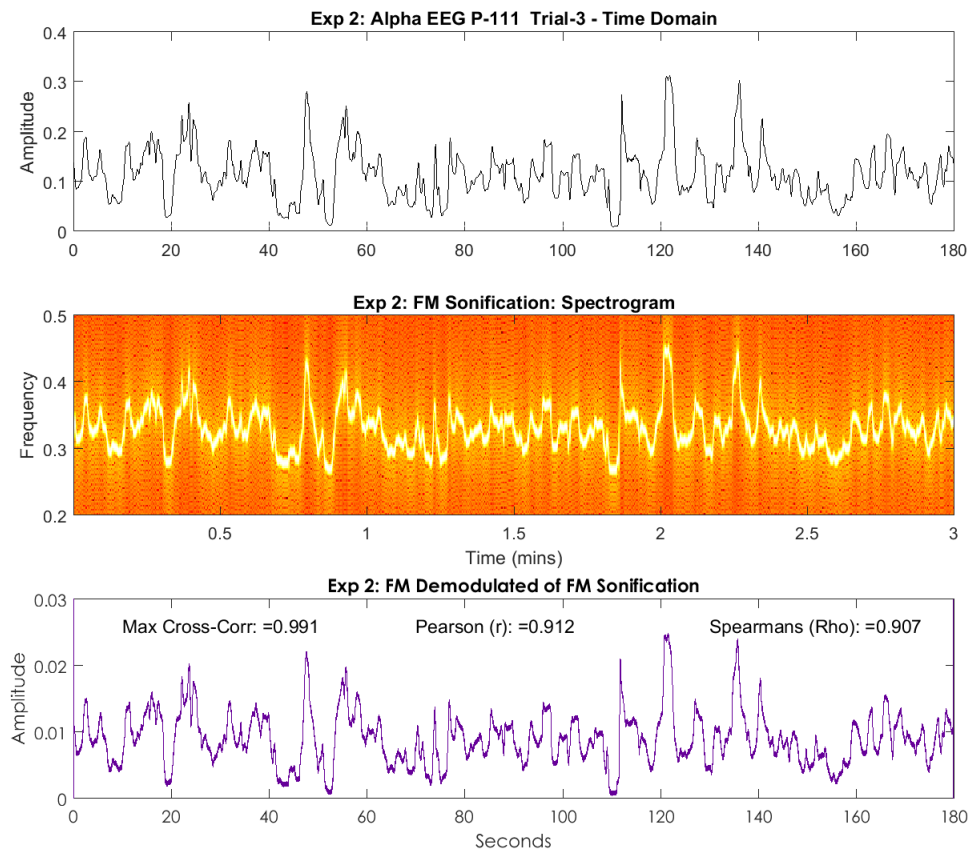
As seen in [figure 5.3.2.2](#), the Pearson's  $r$  correlation between the EEG and the upper amplitude envelope of the AM sonification was 0.918 with a  $p < 0.001$  and the Spearman's Rho was 0.911 at  $p < 0.001$ .





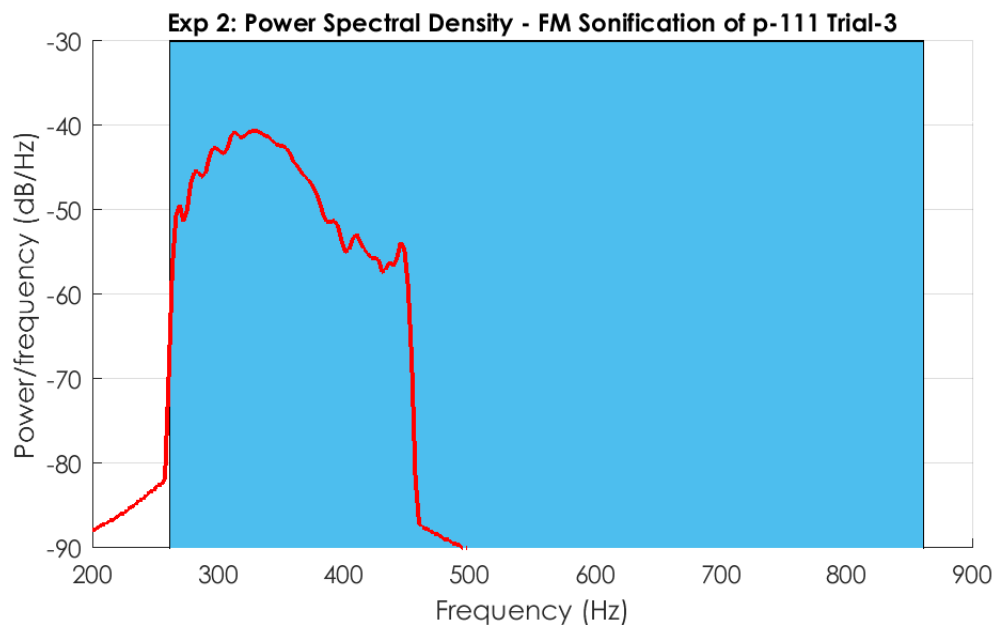
**Figure 5.3.2.3:** Shows the Welch Power Spectral Density Estimate of the AM Sonification from participant 111 in trail 7, vertical grey line shows 261.6 Hz.

**Figure 5.3.2.3**, clearly shows the peak frequency of the AM modulation is 261.6 Hz, with no other extraneous spectral components. Thus this suggests that the Pure Data patch has performed adequately at producing a real-time AM sonification from the EEG data. The next section will present the evaluation of the FM sonification used in experiment 2.



**Figure 5.3.2.4:** Shows the original EEG data in black in the top subplot, the spectrogram (short-time Fourier transform) of the FM sonification with the 261.6 Hz modulation frequency in the middle and the FM demodulated signal in purple on the bottom.

Again as seen in [figure 5.3.2.4](#) all the correlation measures are extremely high, with a Pearson's  $r$  correlation between the EEG and the FM demodulated signal of 0.912 at  $p < 0.001$  and Spearman's  $Rho$  of 0.907 with a  $p < 0.001$ .



**Figure 5.3.2.5:** Shows the Welch Power Spectral Density Estimate of the FM sonification from F3 with the 261.6 Hz modulation frequency. The blue box shows the maximum output frequency range of 261.6 to 861.6 Hz of the FM sonification.

In **figure 5.3.2.5** the output frequency range of the sonification is from 261.6 to around 450 Hz. This output range is dependent on the amplitude of the Alpha EEG that each participant produces and normalized relative alpha measure was taken from the Muse headset with a range between 0 and 1.

Thus looking at both **figures 5.3.2.4** and **5.3.2.5** of the FM sonification, again it can be concluded that the Pure Data patch has performed an adequate job of the FM modulation. But for participant 111 in trail 7 the potential full frequency range of the sonification was not used because they had a relatively low amplitude of Alpha EEG.

### 5.3.3. Participants

Twenty people (ten male and ten female), naive to neurofeedback and not used in Experiment 1, with a mean age of 35.25 ( $SD = 10.3$ ), completed the experiment.

On their arrival, the experiment was explained to the participants and they signed a consent form. No incentive was given and they were informed they could withdraw from the experiment at any time without reason or reprisal and all data would be anonymised. The experiment received ethics approval from The Open University Human Research Ethics Committee number HREC/2015/2011/Steffert/2 and was conducted in accordance with the Declaration of Helsinki.

### 5.3.4. Experimental Design and Procedure

Alpha EEG was recorded from the left forehead for three minutes with eyes closed as a no-feedback baseline. Participants were then asked to rate how "you feel right now" on the 9 questions of the Emotional Rating Scales (for details of the nature of this scale, and the rationale for using it, see [section 5.3.5.1](#) below)

Then participants would hear over external laptop speakers, either the AM or FM sonification of their own real-time Alpha brain waves for three trials of three minutes (i.e. a total of 9 minutes for each sonification) with a short break to blink and stretch between each trial. Participants were instructed to close their eyes and try lowering the amplitude of the AM sonification or to lower the frequency

of the FM sonification. Participants were told to sit still and try and relax, to minimize muscle artifacts that could interfere with the EEG and not to worry if they did not initially have a feeling of control over the sonification.

Success in these tasks corresponds broadly to reducing the alpha activity in the left frontal cortex and the rationale for selecting this aspect of brain activity to be sonified, and how this choice relates to the choice of emotional rating scale was discussed in [section 5.2.1](#) above.

**Table 5.3.4.1** below shows the work flow of the experimental sessions

<b>Sonifications</b>	<b>Time</b>
1. Instructions	2 min
2. Consent	2 min
3. Pre - EEG Baseline	3 min
4. Pre - Mood Baseline	2 min
5. Sonification 1	<b>3 min</b>
6. Sonification 1	<b>3 min</b>
7. Sonification 1	<b>3 min</b>
8. Mid - Mood	2 min
9. Mid - NASA-TLX	2 min
10. Mid - AttrakDiff	5 min
11. Sonification 2	<b>3 min</b>
12. Sonification 2	<b>3 min</b>
13. Sonification 2	<b>3 min</b>
14. Post - Mood	2 min
15. Post - NASA-TLX	2 min
16. Post - AttrakDiff	5 min
<b>Session Duration</b>	45 min

**Table 5.3.4.1:** Shows the Experimental session schedule.

After the three trials in each sonification block the emotion rating scale was used again followed by the NASA-TLX workload questionnaire (as previously described in [Chapter 4.9.3](#)). An additional questionnaire was also used, the AttrakDiff, whose purpose is broadly to measure the hedonic qualities of the experience (as detailed in [section 5.4.3](#) below).

After completing the trials for the first sonification, participants underwent three trials of three minutes for the second sonification followed by the same three questionnaires. The questions were presented in a randomized order within each of the questionnaires. Finally participants were asked their age, gender, if they had done any brainwave training, their musical experience and if they felt they had control over the sonification of their brainwaves.

To control for learning effects over time, the sonifications were presented in a counter-balanced order, with ten of the twenty participants starting with the AM sonification and ten with FM.

Two participants withdrew from the experiment, the first after only two minutes of listening to the AM sonification and the second after listening to all 3 trials of the FM sonification and one minute of the AM. They both found the sound very unsettling and agitating and both reported being very sensitive to sound in general. One participant's data was rejected because she was the only person recruited who had any experience of neurofeedback (It had been intended to do a comparison between novice and expert neurofeedback trainees).

### **5.3.5. Questionnaires**

Three questionnaires were used in Experiment 2 and as in Experiment 1 the questions were presented in a randomized order within each questionnaire, using PsychoPy (Peirce, 2007) open source presentation software.

#### **5.3.5.1. Measure 1: Emotional Rating Scales**

As discussed in [section 2.1.11](#), Russell's circumplex model of affect in [figure 5.3.5.1](#) below (Russell, 1980) suggests that emotional experiences can be

described by two orthogonal factors on a two dimensional plane. The vertical axis represents arousal, which is a measure of how calming or exciting an experience is, while the horizontal axis represents valence, a measure of how negative or positive an emotion is.

In Experiment 1, participants were asked just two questions about the perceived emotional tone of the sonifications: these questions were designed to measure valence and arousal dimensions. By contrast, in Experiment 2, participants were asked, "how do you feel right now", on a 9-question Emotional Rating Scale (see below). The Emotional Rating Scale has more useful properties for the present purposes compared with the simpler scale in at least two respects, as is now explained. Firstly, when making subjective measurements on a two dimensional plane, it can be risky to use just two words or phrases to label two orthogonal axes and assume that everyone will interpret these labels in the same way. An alternative approach is to label eight compass directions on the plane separately and ask separate questions about each. There is still danger of ambiguity, but with eight labels as opposed to two, mutual triangulation helps to reduce this uncertainty. Similarly, many emotional scales assume for example that "Happy" is a bipolar opposite of "Sad". By contrast, the Emotional Rating Scale does not make this questionable assumption of bipolarity, but uses unipolar questions to sample both ends of each dimension (Russell and Carroll, 1999).

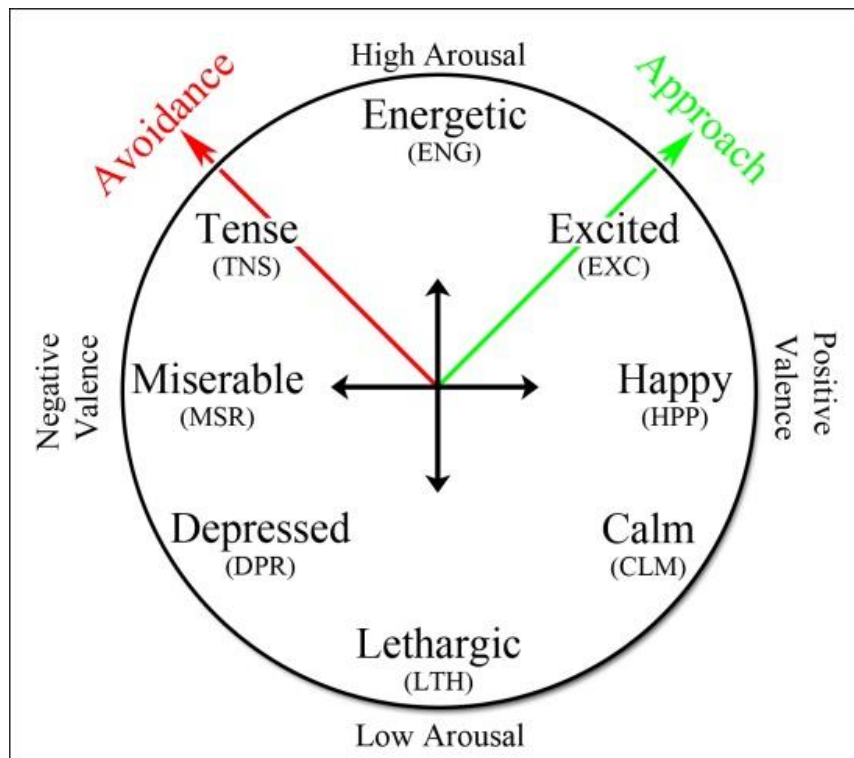
Secondly this new questionnaire tries to measure the 'approach' and 'withdrawal' dimensions discussed in [section 2.1.11](#).

In order to construct Emotional Rating Scales with these two useful properties, eight appropriate words were selected from a range of existing mood and emotion questionnaires, Positive and Negative Affect Schedule (PANAS-X) (Watson and Clark, 1999), Profile of mood states (POMS) (McNair et al., 1989) and Brunel of mood scale (BRUMS24) (Rohlf's et al., 2005).

As well as making it straightforward to look at movement on the four obvious scales representing the extremes of the horizontal and vertical axes on the arousal-valence circumplex - **Happy**, **Lethargic**, **Miserable**, and **Energetic** – this made it easy to separate out movement on the diagonal axes representing avoidance/approach – namely, **Excited**, **Calm**, **Depressed**, and **Tense**.

Thus, participants were asked to rate how “you feel right now” on these 8 scales: in each case on a numeric 20 point scale ranging from 1 “Not at all” to 20 “Extremely”. They were also asked a general ninth question, “Please rate your Overall Mood right now” on the same scale, but ranging from 1 “Bad” to 20 “Good”.





**Figure 5.3.5.1:** Shows the 2-D arousal-valence circumplex with the avoidance and approach axes superimposed in red and green. Around the outside are the 8 emotional adjectives used for the Emotional rating scales used in Experiment 2 (Figure adapted from Knutson et. al (Knutson et al., 2014)).

### 5.3.5.2. Measure 2: NASA-TLX

The NASA **Task Load Index** (NASA-TLX) was the same as in Experiment 1 (see section **4.3.6 Measure 3: Qualitative - NASA-TLX**).

### 5.3.5.3. Measure 3: AttrakDiff

When trying to assess the efficacy of any human computer interface, like a neurofeedback system, whether it uses visual or auditory feedback, it is not simply a measure of the time taken to complete the task or number of errors,

that defines its effectiveness, but how the user feels about the system and the interaction, or the so called hedonic factors.

Thus, there could be a situation where there was a **beautiful** sonification but the process making it sound nice has lost much of the information content and the user cannot get any control over the sound, or an **unpleasant** sonification that the user could quickly learn to control but could not tolerate for more than a minute.

In neurofeedback scenarios, potentially requiring long-term use, these hedonic and aesthetic factors could significantly affect how a person feels about the interaction with the sonification and therefore effect the compliance and up-take of the neurofeedback intervention.

Therefore the third questionnaire, introduced in Experiment 2, was the AttrakDiff which is a measure of the User Experience of an interaction with software or a product. It has 28 contrasting pairs of words (e.g. "confusing - clear", "unusual - ordinary", "good - bad") which relate to four hypothesized underlying dimensions, as follows. Firstly, **Pragmatic Quality (PQ)** is equivalent to a typical usability measure like, usefulness and usability.

Secondly, **Hedonic Quality - Identity (HQ-I)**, is a measure of the user's identification with the product or interaction, such as can people identify with the product.

Thirdly, **Hedonic Quality - Stimulation (HQ-S)**, is a measure of how much scope for exploration the product or interaction gives, such as is curiosity encouraged.

Finally, **Attractiveness (ATT)** is a general measure of the product's "Desirability".

Hedonic Quality (HQ)	Too Self-Oriented	Self-Oriented	Desired
		Neutral	Task-Oriented
	Superficial		Too Task-Oriented
Pragmatic Quality (PQ)			

**Table 5.3.5.3:** Show the interaction of the Hedonic Quality (HQ) on the y-axis and Pragmatic Quality (PQ) on the x-axis.

In [table 5.3.5.3](#) for example a product interface that was low on both Pragmatic Quality and Hedonic Quality factors would be considered as 'Superficial' but one high on both would be 'Desired'.

Each word pair (See [Figure 5.4.3](#)) is rated on a seven point scale, ranging from -3 to 3 with zero in the middle. The AttrakDiff is designed to measure the user experience of interactive products and does not appear to have been used before in EEG sonification. Therefore the AttrakDiff was used in Experiment 2 to see if it could assess the nature of interaction with the sonification of the EEG neurofeedback and whether a smaller sub-set of questions could be identified for EEG sonification applications. (For a full list of the 28 contrasting pairs of words (see [Figure 5.4.3](#)).

## 5.4. Results

For Experiment 2 the same statistical analysis corrections were used as in Experiment 1. The Alpha level was fixed at 0.05 for all statistical tests. Greenhouse-Geisser correction was used to correct for unequal variances. For multivariate analysis Wilks' Lambda L was used as the multivariate criterion. All variables were normally distributed according to the Kolmogorov-Smirnov test.

For the **AttrakDiff** questionnaire the 7 questions from each of the 4 dimensions were averaged - PQ, HQ-I, HQ-S, ATT. The EEG relative alpha power from Muse was averaged across 3-min presentation for the baseline and three trials of AM and FM sonifications. In all the analyses, between-subjects factor of sonification presentation order was used but no significant effects were seen thus assuring this factor did not interfere with other results.

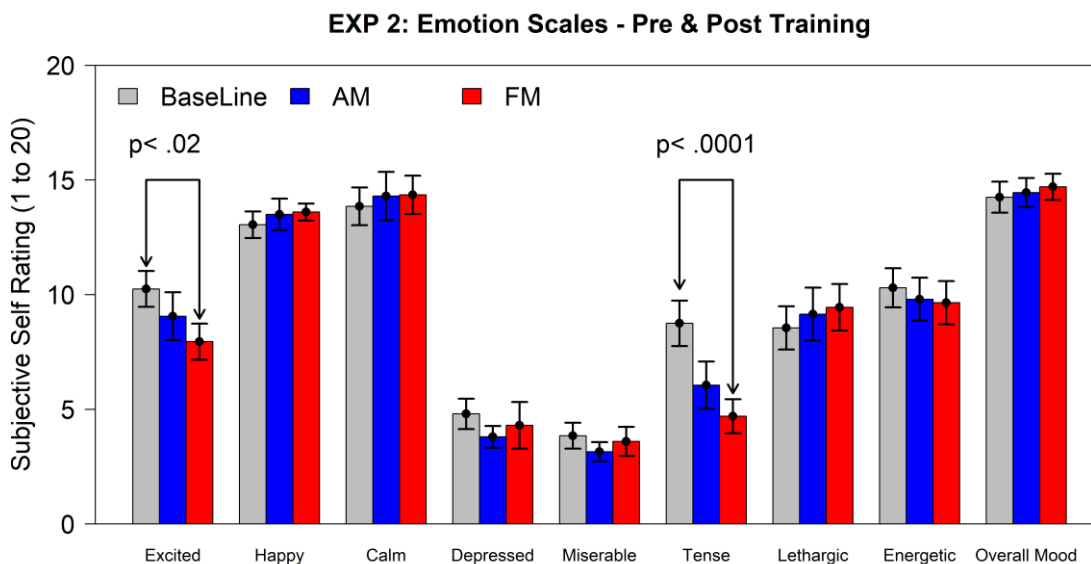
In SPSS, three separate mixed MANOVAs for **NASA-TLX**, **AttrakDiff**, and the **Emotion scales** were run on the subjective **qualitative** data. For the NASA and AttrakDiff the design was 2 (two presentation blocks) x 2 (AM vs. FM). For Emotion scales the design was 2 (two presentation blocks) x 3 (baseline vs. AM vs. FM). For the EEG an ANOVA with a 2 (two presentation block) x 2 (AM vs. FM) x 3 (three trials) design was computed. Importantly, there was no effect of presentation order for any of the measures.

### 5.4.1. Emotional Rating Scale

For the Emotion Rating scales, multivariate statistics did not reach significance. For the individual dimensions, only two scales showed any significant difference between baseline and the FM trials. For the "**Excited**" scale, difference from baseline was close to significance at  $F(1.6, 29.6) = 2.89$   $p = 0.08$ ,  $\eta^2 = 0.138$ .

Bonferroni-corrected pairwise comparisons showed that the largest change from the baseline ( $M = 10.3$ ,  $SE = 0.8$ ) was after the FM condition ( $M = 8.0$ ,  $SE = 0.8$ ),  $p < 0.02$ . For the “**Tense**” scale there was also significance  $F(1.7, 30.67) = 8.30$ ,  $p < 0.002$ ,  $\eta^2 = 0.316$ . Post-hoc comparisons again showed that the significant difference occurred between baseline ( $M = 8.8$ ,  $SE = 0.9$ ) and FM condition ( $M = 4.7$ ,  $SE = 0.7$ ),  $p < 0.0001$ . **Figure 5.4.1** shows the scores for all nine scales.

As anticipated, training down the alpha power of the left frontal cortex did reduce activation of the avoidance axes as indicated by the lower “Tense” scores and although there was also a decline in “**Excited**” scale, this was a differential effect as none of the other emotional ratings changed for either the FM or AM conditions.



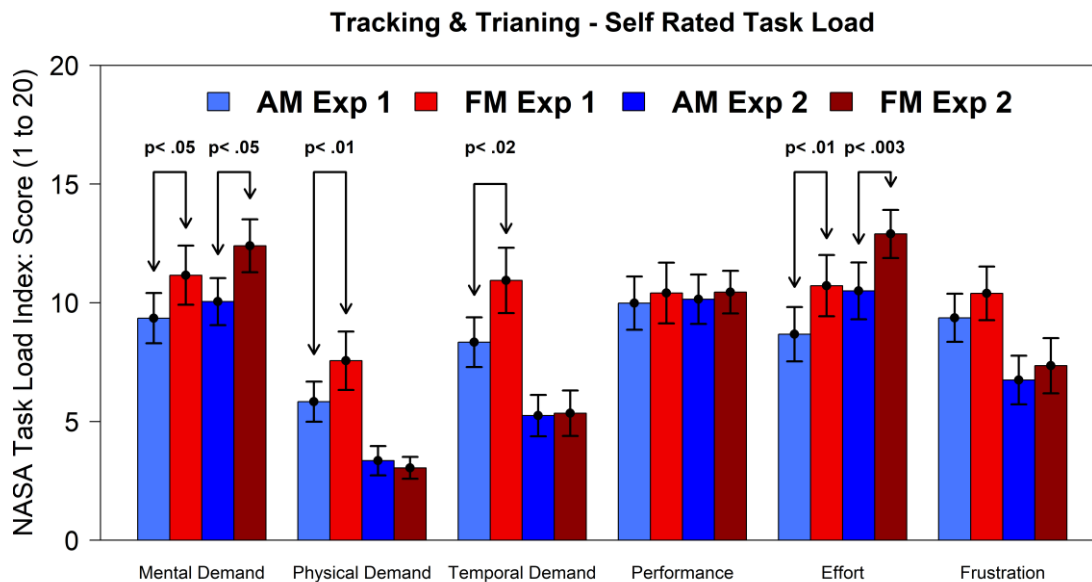
**Figure 5.4.1:** Subjective ratings on emotion scales: The grey bars show the baseline, bleu bars show the AM condition and the red bars show the FM condition. The error bars show Standard Error and the numbers above the bars

*show the p-values for the statistically significant differences between baseline and FM.*

#### **5.4.2. NASA-TLX**

For NASA-TLX, multivariate statistics did not show a significant difference between AM and FM sonifications. For the individual dimensions, only two scales showed a difference in this regard for both experiments. For Experiment 2 in the FM condition, Mental Demand was significantly higher at  $F(1, 18) = 4.53$   $p < 0.05$ ,  $\eta^2 = 0.201$  (see [Figure 5.4.2](#) for details). The FM condition was also rated as requiring more Effort than the AM condition with significance of  $F(1, 18) = 5.53$   $p < 0.003$ ,  $\eta^2 = 0.235$ .

However, Physical and Temporal demands and Frustration were unsurprisingly reported as lower in Experiment 2 since there was no physical tracking task. Finally, the Effort scale appeared to be the most sensitive at detecting difference between the sonifications, with both experiments demonstrating subjective preference for AM-based sonification. Intriguingly the subjective rating of Performance did not vary much over all sonifications in both experiments.



**Figure 5.4.2:** The vertical axis shows the mean of the subjective ratings for the six questions of the NASA-TLX: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration each on a 20 point scale. The error bars show Standard Errors. The numbers above the bars show the p-values for the statistically significant differences between AM and FM. The blue bars show the ratings for AM with light blue being Experiment 1 and dark blue Experiment 2. Red bars show FM scores, with light red representing Experiment 1 and dark red representing Experiment 2.

### 5.4.3. AttrakDiff

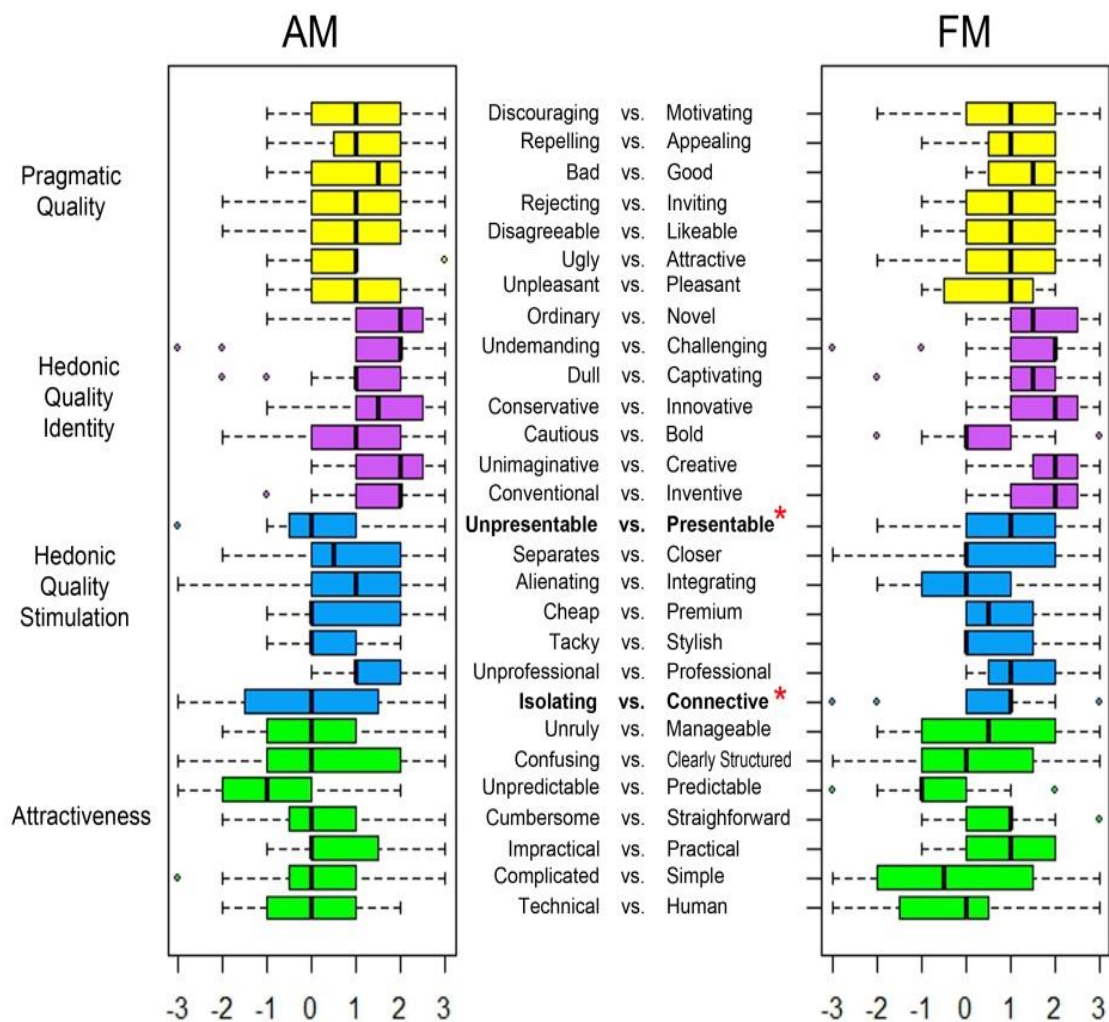
The MANOVA based on the AttrakDiff questionnaire did not show any statistically significant difference between the sonifications, nor did separate univariate statistics for the four dimensions. The averaged values for the four dimensions of the AttrakDiff for AM and FM modulation respectively were as follows:

PQ:	AM 0.15	vs.	FM 0.17	(SE = 0.2);
HQ-I:	AM 0.61	vs.	FM 0.75	(SE = 0.2);
HQ-S:	AM 1.4	vs.	FM 1.4	(SE = 0.2);
ATT:	AM 0.96	vs.	FM 1.01	(SE = 0.2).

Additionally, all of the 28 questions shown in [Figure 5.4.3](#) were tested for any statistical variations from zero (In other words for a willingness to assign a preference in either direction). For most of the questions from the **Pragmatic Quality** and **Hedonic Quality-Stimulation** dimensions did not differ from zero ( $t < 1$ ). However, all answers to questions from the **Hedonic Quality-Identity** and **Attractiveness** dimensions were significantly different from 0, demonstrating a potential sensitivity of these two dimensions to evaluate EEG sonification interaction.

Finally, when comparing AM and FM-based sonifications for each question, two items from Hedonic Quality-Stimulation, namely isolating/connective and unpresentable /presentable showed trends ( $p = 0.1$ ) in favour of FM modulation (see [Figure 5.4.3](#) below). This dimension concerns product novelty, presentation style and interest from the user perspective.





**Figure 5.4.3:** Four dimensions of AttrakDiff and corresponding 28 questions for AM and FM-based sonification. Error bars show the minimum and maximum and the dots show outliers (Where the score is more than the range times the interquartile range). The actresses highlight the two items that showed trends ( $p = 0.1$ ) in favor of FM.

#### 5.4.4. Electroencephalography

Due to the short duration of the training session and the within subject design where each participant heard both sonifications, it was not necessarily

anticipated that there would be a statistically significant group level difference between the Pre and Post EEG Alpha power. However as the two sonification methods were being compared head-to-head it was hoped there would be a differential effect between the two sonifications and/or with the mood scale and task load measures.

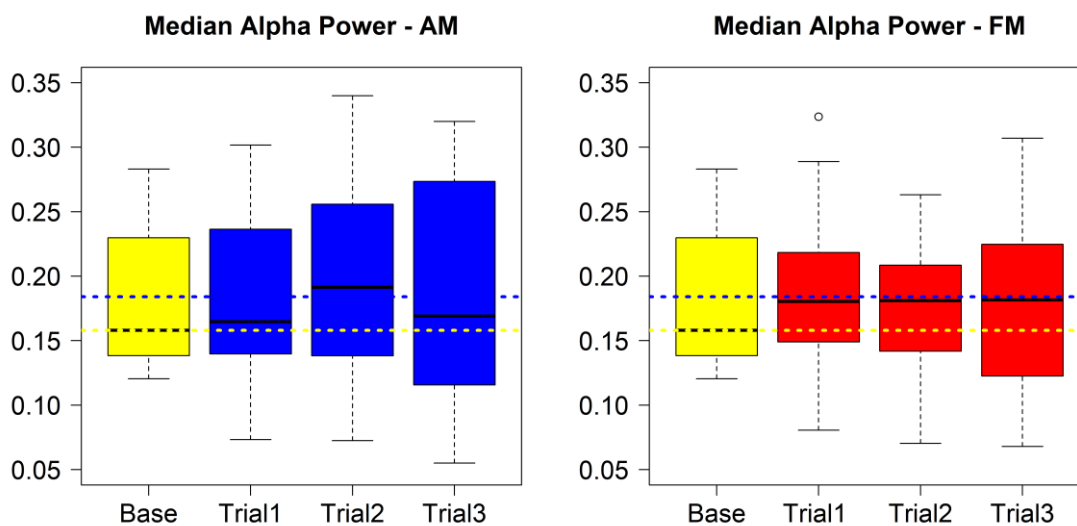
**Table 5.4.4.1** shows the Quantification of alpha activity of the seven EEG trials and presents means and standard error values across 20 participants.

<b>Trials ID</b>	<b># of alpha bursts</b>	<b>Mean duration bursts [s]</b>	<b>alpha</b>	<b>Excess kurtosis</b>	<b>Skewness</b>
<b>BAS</b>	38.35 [1.2]	2.15 [0.74]		0.66 [0.3]	0.66 [0.11]
<b>AM1</b>	30.60 [2.4]	2.81 [0.51]		1.22 [0.37]	0.81 [0.10]
<b>AM2</b>	31.70 [2.3]	29.78 [5.39]		0.41 [0.23]	0.56 [0.10]
<b>AM3</b>	29.65 [2.7]	33.94 [10.39]		0.48 [0.34]	0.64 [0.10]
<b>FM1</b>	32.25 [2.0]	27.64 [3.80]		0.86 [0.53]	0.66 [0.14]
<b>FM2</b>	31.40 [2.5]	24.97 [3.58]		1.75 [0.64]	0.87 [0.13]
<b>FM3</b>	28.90 [2.4]	29.29 [6.35]		0.88 [0.28]	0.72 [0.10]

**Table 5.4.4.1:** Shows the average EEG Alpha activity in the seven trials for all 20 participants with their eyes closed in the baseline (BAS) and the three AM and three FM sonification neurofeedback trials. The number of alpha bursts is smaller in all the trials than the Baseline whereas the mean duration of the alpha burst is greater.

A mixed 3 x 2 x 2 ANOVA analysis of EEG data was calculated on the averaged alpha power. Between-subject factor was the sonification presentation order, and within-subject factors were 3 repetitions and 2 types of sonifications (AM vs. FM). The difference between two sonifications did not reach significance with  $F(1, 18) = 0.18$   $p = 0.7$ ,  $\eta^2 = 0.01$ .

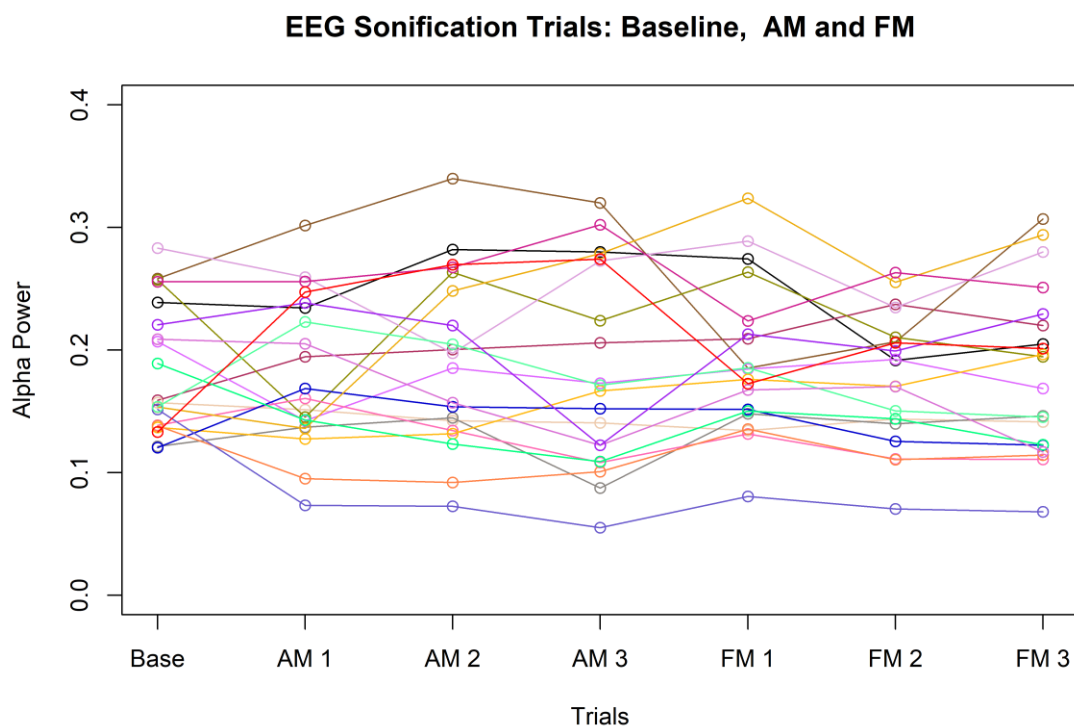
The grand means of relative alpha power averaged across 3 repetitions were **0.175** (STD = 0.07) for **AM** and **0.181** (STD = 0.06) for **FM**-based sonifications. There was also no effect observed from the repetition of the task, i.e. no better performance for the last trial. The Median of the Median values shown in [Figure 5.4.4.2](#) for the **baseline** session was **0.158** (STD = 0.053). For the AM Trial 1: **0.165** (STD = 0.061), Trial 2: **0.191** (STD = 0.070), Trial 3: **0.169** (STD = 0.080). For FM Trial 1: **0.180** (STD = 0.061), Trial 2: **0.181** (STD = 0.052), Trial 3: **0.182** (STD = 0.067).



**Figure 5.4.4.2:** Box-&-Whisker plot of the 'Median Alpha Power' of the Baseline trial (In yellow, and is the same trial in both plots) and the AM sonification trials (Left: in blue) and the FM sonification trials (Right: in red). The bottom and top of each box show the first and third quartiles, (i.e. 25% and 75%). The whiskers show the minimum and maximum values. The black line gives the median of each

trial. The yellow dotted line is the median of the 'Baseline' trial and the blue dotted line is the mean of the 'Baseline'.

The objective of the neurofeedback was to train down the **Alpha Power**. But as can be seen in [figure 5.4.4.2](#) the trial medians were all above the Baseline median. Furthermore the variance of the alpha power was greater and increased over the trials in the AM condition. In [figure 5.4.4.2](#) shows a line plot of each individual over the trials.



**Figure 5.4.4.3:** Shows an individual line plot of the Alpha power of each of the 20 participants in the baseline and for the three AM and three FM training trials. (Note that for half the participants the FM trials came before the AM trials)

In [figure 5.4.4.3](#) it can be seen that many people are able to reduce their alpha activity from baseline but clearly many were not able to.

## 5.5. Discussion

This chapter presents a second experiment that compared the same two deliberately simple AM and FM-based EEG sonification methods as in experiment 1, but this time with a single session of real-time neurofeedback.

Neurofeedback studies usually take a number of training sessions and often take months to complete. Here a single session of real-time EEG sonification neurofeedback in Experiment 2 was used to validate the findings of Experiment 1 (which had relied on pre-recorded EEG). In this way, the relative abilities of two specific sonifications could be assessed by both experiments, and any potentially predictive relationship of the tracking task to the real-time neurofeedback session could be assessed.

Experiment 2 extended the evaluation of the same two sonifications into a real-life neurofeedback training environment where participants were engaged in an emotional regulation task by training down left frontal alpha in order to reduce negative emotions (also known as “reducing avoidance or withdrawal behaviour”).

As in Experiment 1, the NASA-TLX Task Load Index questionnaire showed a preference for AM over FM based sonification. However, the emotion rating scales showed that FM-based sonification yielded a stronger reduction in negative emotions. The change in the rated emotional state could be seen as an indirect corroborative measure of the FM sonification's effectiveness. The preference for Frequency Modulation by itself is not surprising because pitch-based sonification is the most widely used method in many different domains that use sound to represent dynamic data (Dubus and Bresin, 2013).

Unfortunately, no significant concomitant reduction of EEG alpha activity was observed in Experiment 2. There could be a number of possible reasons why the physiological data did not show results corresponding with the subjective ratings. One pessimistic view might be that neither of the sonifications are appropriate for conveying EEG data. Perhaps the fact that most people did not like the sounds could have inhibited learning - although this is unlikely, since the other emotional rating scales, such as happiness, did not change during the course of Experiment 2. It could also be the case that the training session was too short. More specifically, it could be that a single session is not enough time for participants to associate changes in the auditory signal to changes in their brain, and then learn to modify their brain activity. Although Hardt and Kamiya (Hardt and Kamiya, 1978) did show changes in alpha with one session of EEG sonification, this was with highly anxious people, who would feel calmer if their alpha levels increased. In the present study, partly for ethical and partly for practical reasons, it was not possible to work with a clinical population.

Alternatively, it could also be that hearing both AM and FM-based sonifications in the same session may have confused the participants. Finally, it could be that the EEG parameter chosen does not actually reflect the emotional states being assessed by the questionnaire. But the fact that the emotion ratings did change without the concomitant statistically significant reduction in alpha power may also reflect that summary statistics on a 3 minute epoch of EEG (in this case the median of the EEG alpha power) does not adequately capture any changes in the temporal dynamics of the data. Despite not being a double-blind study, the possibility of these changes coming from the placebo effect seems unlikely as the participants were not informed as to the nature of the expected

changes in emotional ratings, or even that the emotions were likely to change as a result of reducing the alpha power. Of course, the fact that they were asked to fill in a nine factor emotional rating scale after each sonification would arguably give an indication of the aims of the experiment but there were no changes in seven of the other factors from baseline or between sonifications.

While the aesthetic aspect of sonifications was not directly addressed in this experiment, it is important to note that only a few participants liked the sounds of the AM and FM sonifications, and some vehemently disliked them. Echoing the reaction in the earlier experiment, two participants terminated their involvement in the experiment for this reason. At the same time, the AttrakDiff questionnaire used in this experiment showed the trend that FM-based modulation was perceived as being more novel and interesting.

This present experiment addresses four limitations commonly found in EEG sonification experiments, as follows:

- Many experiments use solely subjective preferences to measure a sonification's effectiveness;
- In many experiments, trained participants are simply asked to identify a particular kind of abnormal sonification recording. Some of these studies show good detection accuracy but such methods do little to reveal how well a particular sonification allows the temporal aspects of the data to be perceived and how effective it might be in neurofeedback;
- Psychoacoustic studies in general tend to use very short sound clips that may not capture the temporal dynamics of brain behaviour or a typical sonification neurofeedback session. For example, the International Affective Digitized

Sounds (IADS) database (Stevenson and James, 2008) hosts a large collection of normative emotional stimuli, consisting of sounds that are only six seconds in duration;

- A questionnaire administered at the end of a 3-minute listening period is incapable of capturing the full temporal dynamics of a listening experience and cannot help disambiguate the relative abilities of a sonification to convey the EEG data.

Furthermore this experiment presents a head-to-head comparison of two well-known sonification techniques on a range of assessment tools, so could have implications for the general domain of sonification, not just for the display of EEG.

Both experiments used Open Source software such as PsychoPy for the tracking task and questionnaire presentation and Pure Data for the sonifications in order to facilitate replication and stimulate research to build a database of quantitative assessment of different sonifications, which could in turn become a valuable resource for the development of the field of EEG sonification.



## Chapter 6: Experiment 3

A real-time, two channel, frontal alpha EEG asymmetry tracking and training experiment with amplitude and frequency modulation sonification.

### 6.1. Introduction

This chapter presents the third and final EEG sonification experiment. See [section 6.1.2](#) for the detailed motivation for this experiment. In outline, the experiment was designed to test the extent to which healthy adults, who have not done neurofeedback before, can learn to modify their own frontal Alpha EEG with the use of two simultaneous channels of real-time EEG sonification neurofeedback. Two different sonification techniques were used to test for differential learning outcomes, in order to elucidate salient properties of the sonification that could be appropriate for the presentation of the EEG data. A mixed between- and within-subject design was used.

The experimental design consisted of two phases. Firstly, there was a tracking phase, where participants were asked to listen to a pre-recorded EEG and try and track the activity of the sonification using a physical slider (not a mouse, as in experiment 1).

This was followed by a training phase, where participants were instructed to try to modify their own brainwaves by listening to a real-time sonification of their own alpha EEG activity. Each participant conducted two experimental sessions, each of approximately 1 hour duration, one for each sonification. The NASA Task load Index (NASA-TLX) was administered after each tracking and

training task, and a 9 question mood survey was given pre and post of the training task.

#### **6.1.1. Research questions for experiment 3**

The four research questions for experiment 3 were as follows:

**EQ6.1).** Can real-time sonification of two channels of alpha EEG help people learn to modify their own simultaneous frontal alpha asymmetry brain wave activity? (Explained in [section 6.2](#))

**EQ6.2).** Will there be a decrease in avoidance or increase in approach type behaviour with two channel real-time frontal alpha asymmetry sonification neurofeedback? (A behavioural indication of mood change – see [section 6.2](#))

**EQ6.3).** Will the two different techniques of two channel real-time frontal alpha asymmetry sonification neurofeedback have different learning outcomes?

**EQ6.4).** Can a person's ability to track a two channel sonification of alpha EEG with a physical slider predict their performance in a real-time, two channel alpha EEG sonification neurofeedback training task?

#### **6.1.2. Motivation for Experiment 3**

This third experiment is both a consolidation and an extension of the previous two experiments. In experiment 1, participants tried to track the activity of a single audio channel of either amplitude modulation (AM) or frequency modulation (FM) of alpha EEG sonification with a mouse and a slider on a computer screen. Participants did several trials of both sonification methods in one session.

The second experiment used the same two sonification methods but this time in a real-time neurofeedback session and again participants received both sonification methods in a single session.

When looked at together, the first two experiments allow a comparison between the two sonification methods on a within subject level, but can also give some information on how performance on the tracking task can compare or predict the performance in the neurofeedback task in a between subjects design.

One obvious issue with the first two experiments when viewed together is that the participants were different in both experiments. A second potential criticism is that having the two different sonification methods in the same session could create either interference or learning effects that would change the outcomes of the second sonification that was presented.

In order to address these issues, this third experiment consists of two parts in the same session. Firstly, a tracking component similar to experiment 1, where participants listen to a pre-recorded EEG sonification and try to track the activity with a physical slider in real-time, and secondly a real-time EEG sonification neurofeedback training experiment, similar to experiment 2.

Participants conducted two experimental sessions and each session consisted of only one sonification method at a time. Each session was around one hour in duration, a week or more apart and participants were randomly assigned to receive either AM or FM sonification in the first session, followed by the other sonification in the second session.

This third design allows a within-subject observation of both how the tracking task can predict the training outcomes, and a comparison between the two different sonification methods. It is hoped by using a counter balanced design with the two sonification methods in separate sessions and allowing a week or more between each session, this will eliminate any potential interference or learning effects between the two sonification methods. The increased power of a within-subject design could also help to determine whether the tracking task could be a useful proxy for assessing a sonification's suitability for neurofeedback.

The field of EEG sonification for neurofeedback is still at an early stage and progress will require developing and testing many new EEG sonifications. But the conventional testing method of running a randomised double-blind placebo-controlled study with 30 participants, carrying out ten or twenty neurofeedback sessions for each new sonification method would be disproportionately onerous. If the proposed tracking task were found to be able to predict the potential of particular sonifications for neurofeedback, this might save a great deal of work for many researchers in the development and testing of future sonifications.

The fact that most neurofeedback studies typically run multiple sessions of feedback for each participant does highlight the biggest risk for this experiment, the fact that only one neurofeedback training session per sonification was conducted by each participant. Multiple sessions are generally seen as needed for effective neurofeedback, since this is typically what is required for reliable learning effects to be observed. However, this limitation is

hard to avoid in the present case, given the inevitable limitations of a PhD study and the cross disciplinary nature of the research.

But as highlighted in the literature review there are some studies from the early days of neurofeedback in the 1960s that have shown significant changes in both EEG and psychometric questionnaires with a single session of EEG sonification neurofeedback, while a recent fMRI neurofeedback study has shown that people with Major Depressive Disorder can learn to self-regulate their amygdala response, resulting in improved mood with a single session of fMRI neurofeedback (Young et al., 2014). So it is not unreasonable to look for a statistically significant change in EEG or psychometric rating scales within one session.

## **6.2. Two-channel and two sonifications**

One of the deliberate limitations of the first two experiments was the use of a single auditory stream of EEG sonification, but as discussed in [section 2.3](#), one of the primary motivations of exploring the use of EEG sonification for neurofeedback is the potential to convey multiple streams of EEG data.

Therefore in experiment 3, it was decided to explore two simultaneous audio streams of two EEG channels. [Section 6.2.1](#) below (and the paragraph that precedes it) will discuss the mappings to be used for the sonifications. As will be made clear in those discussions, the frontal alpha asymmetry neurofeedback training protocol, explained in [section 2.1.10](#), is particularly well suited as a vehicle to demonstrate the potential utility of two-channel EEG sonification.

As explained in [section 2.1.10](#), EEG alpha amplitude is inversely correlated with oxygen and glucose consumption, thus it can be seen as an index of inactivity or inhibition. Given the Davidson model of affective cognition (See [section 2.1.10](#)) that the right prefrontal cortex is responsible for processing negative or withdrawal type behaviour, whereas the left prefrontal cortex processes positive or approach behaviour, frontal alpha asymmetry can be a real-time measure of cognition related to approach and withdrawal, i.e. a real-time measure of mood.

The question now arises of how to present two concurrent audio streams of EEG. One obvious way is to present one stream to each ear. This would be an excellent metaphorical fit with the frontal alpha asymmetry task, in that the EEG alpha amplitude on the left side of the brain could be presented to the left ear and the right side activity to the right ear.

The task of frontal alpha asymmetry neurofeedback training is to either increase the alpha amplitude in the right prefrontal hemisphere or to decrease the alpha amplitude in the left, or both of these at once. Therefore giving rise to an activation of the left and/or a decrease in activation of the right prefrontal cortex should lead to an increase in positive affect or mood.

### **6.2.1. AM and FM sonification mapping**

In the first two experiments, the mapping of the EEG signal to the output range of the Amplitude Modulation (AM) and Frequency Modulation (FM) sonifications (see [section 1.4.3](#)) was selected by experimentation. Output ranges were chosen in order to convey the greatest dynamic range of the EEG

possible without exceeding the range of human perception and without making the sonification too irritating for the participants to listen to for 9 minutes.

A potential criticism of this approach is that it could create an 'unfair' comparison between the two different sonification techniques. One sonification may have a mapping that produced a greater range of sound outputs so the fact that it is rated as a better sonification is not because of the technique, but the output range of the mapping. This criticism suggests limiting all sonifications so that none has a wider range.

On the other hand, it could be argued that the whole point of some sonifications is that they take advantage of the nature of the auditory perception system to map a wider frequency range of EEG with higher resolution than is possible with some other mapping. Thus, the comparison should be between different sonification methods as each might be used to best advantage in the real world. A sonification able to convey a greater range of EEG data could increase learning in an EEG sonification neurofeedback task and it would be unrealistic to limit the output range of one sonification just to make a 'fair' comparison. The key proviso according to this point of view is that the output range for each sonification should be chosen to show that technique to its best advantage, as far as reasonably possible.

Any experiment of this kind will inevitably leave empirical questions open, and the point of the tracking task is that, despite having some obvious drawbacks, the research has to start somewhere. It will require dozens if not hundreds of empirical studies to comprehensively identify which parameters in a sonification

will be more useful to convey an EEG parameter and which EEG parameters are best suited for sonification.

The above issues raise the question of what aspect of sonification needs to be tested and what constitutes a reasonable comparison. Particularly given there is no ground truth to work from.

Thus it was decided in order to create a comparison of usable output range between the two sonifications and to make the studies easier to interpret, the two sonifications would be made more “**perceptually equivalent**”, in a sense which will be explained next.

Thus, in the next two sections, the potential available perceptual output ranges for AM and FM sonifications are considered in turn, starting with AM sonifications.

### 6.2.2. AM Sonification and Loudness

The Human auditory system has an exponential perception of loudness and a perceptual range from around 0 dB(A) to 120 dB(A) (Moore, 2012, p. 127).

Preliminary testing for this third experiment with white noise, pure tones and EEG sonification signals, established that the background noise of the testing rooms was around 30 dB(A) and a test signals could not be ‘confidently’ heard till a minimum level of 40 dB(A) was reached.

Furthermore, although the reported maximum acceptable loudness level is given in the range of 90 to 110 dB(A), it was decided to set the maximum loudness to 80 dB(A), because of the potentially irritating nature of the EEG sonifications, given that this experiment requires the participants to continually



attend to the audio stimulus for 4 minutes at a time. This experiment is unlike many auditory perception tasks, where a participant merely has to wait for a simple short audio tone before pushing a button.

Therefore the loudness of the sonification output from the system was set to remain within a range of 40 to 80 dB(A) as tested using a pure tone carrier wave with a frequency of 261.61 Hz (the tone used in the AM sonification). This was done by setting the laptop sound card to the maximum level with a sound meter testing the minimum and maximum values into the sonification equation to generate the given output range. Consequently the minimum input value was 0.001 and the maximum was 0.12. This means that when the maximum value of EEG is entered into the sonification equation the output will equal 0.12 and the loudness of the system will be 80 dB(A).

### **Just Noticeable Difference of loudness (JND-dB(A))**

Despite an extensive history of psychoacoustic experiments over the last 150 years it has been difficult to extract definitive findings for human perceptual response to loudness and frequency. One often quoted rule of thumb for the just noticeable difference of amplitude is 1 dB(A) and this was confirmed as a reasonable value on 4 subjects using the continuous pure tone of 261.61 Hz used in the AM sonification for the present experiment. Thus with a loudness range of 40 to 80 dB(A) this gives 40 perceptually equal steps with a Delta I of 1 dB(A).

### **AM Sonification Transfer Function**

Hermann recommended a textual notation method called an “assignment table” for presenting the mapping function of a sonification in a human-readable method (Hermann et al., 2002, p39). Here is an example mapping in that notation:

**Alpha power [0, 40] (uV<sup>2</sup>) - exponential → Amplitude [40, 80] dB(A)**

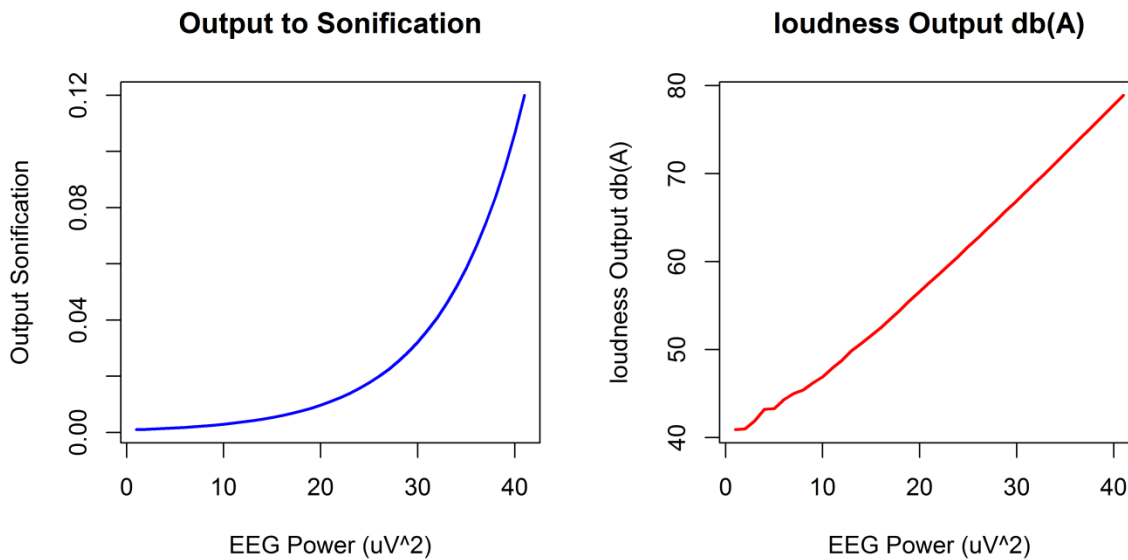
This means that an input of the EEG alpha power in a range of 0 to 40 uV<sup>2</sup> (EEG power measured in micro-volts squared) is exponentially mapped to an audio amplitude output of 40 to 80 dB(A).

This mapping uses an exponential Transfer Function Equation for Amplitude which maps the varying power logarithmically into a range between a pre-chosen maximum and minimum amplitude output as follows:

$$\text{Amplitude} = 10.^{((\log(A_{\text{max}}) - \log(A_{\text{min}}) * \text{EEG}/\text{EEG}_{\text{max}} + \log(A_{\text{min}}))}$$

(Eq. 6.2.2.1)

Where the A\_min = 0.001 and the A\_max = 0.12 (derived from the testing as discussed about) and EEG is the Alpha EEG power input signal and EEG\_max is the maximum amplitude of the EEG for each person (as measured in the baseline). So for the input range of the Alpha EEG of 0 to 40 uV<sup>2</sup> (X-axis on the left-hand plot in [figure 6.2.2.1](#)) the output of the sonification equation will be 0.001 to 0.12 (Y-axis on the left-hand plot) and this will give an audio amplitude output of 40 to 80 dB(A) which will be perceived as a linear increase in amplitude (red line in right hand plot).

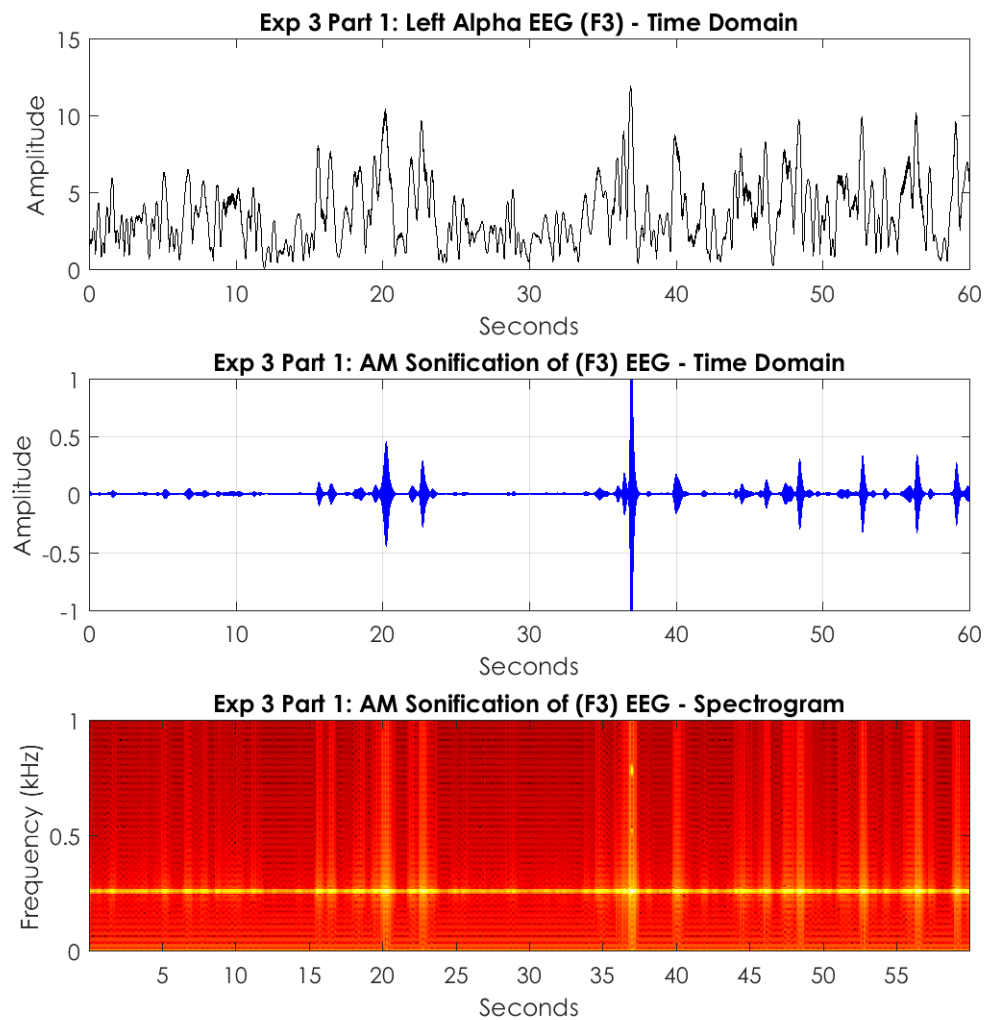


**Figure 6.2.2.1:** Left: shows the AM sonification transfer curve given by equation Eq. 6.2.2.1. The blue line shows the output of the sonification equation on the Y-axis for a given input of EEG power on the X-axis. Right: the red line shows a perceptually linear output of the sonification system, as measured by a sound meter in dB(A) on the Y-axis and the X-axis shows the EEG power input in to the sonification equation.

In the example above, an increase of 1  $\mu V^2$  of EEG equates to 1 dB(A) of loudness, but in practice the maximum amplitude of Alpha that each person produces is very variable, so it is necessary to personalise the EEG input range. During each baseline EEG recording, the maximum Alpha amplitude was calculated and the value was entered into the sonification software to scale the loudness range output to the Alpha EEG range input (See [figure 6.2.4.1](#) of the sonification software interface below).

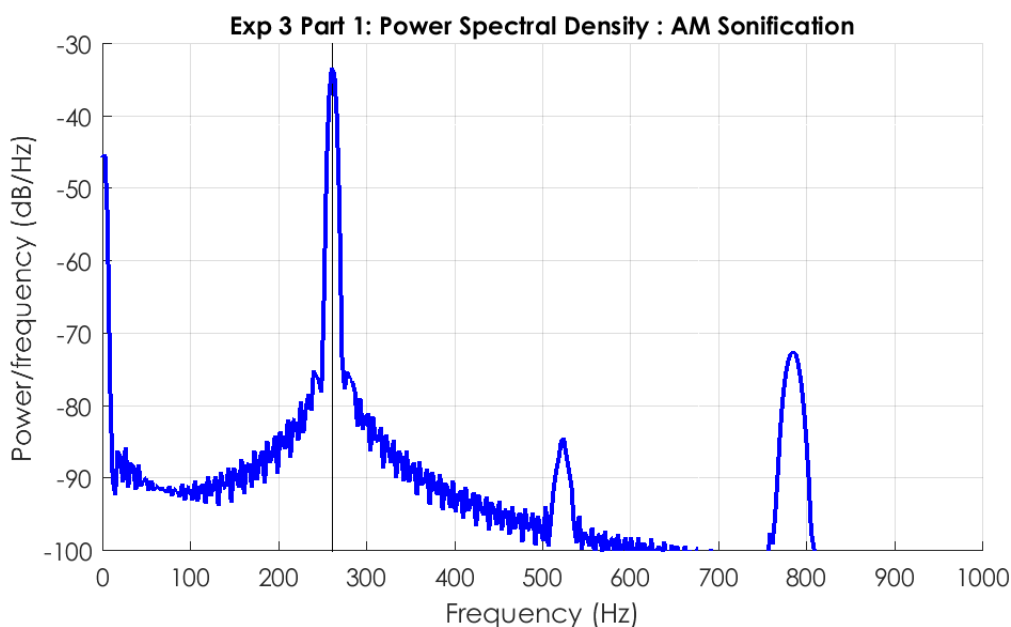
Thus the AM sonification mapping should give 40 approximately equal 'just noticeable difference' steps across the Alpha EEG range.

The sonifications for the tracking task in part 1 of experiment 3 were made in Pure Data with pre-recorded Alpha EEG data from the Mitsar, using the above equations and [figure 6.2.2.2](#), shows the EEG and its sonification of the left channel (F3).



**Figure 6.2.2.2:** Shows the original Alpha EEG from F3 on the top subplot. The sound output from the AM sonification with the 261.6 Hz modulation frequency in the middle and the spectrogram of the sonification, on the bottom.

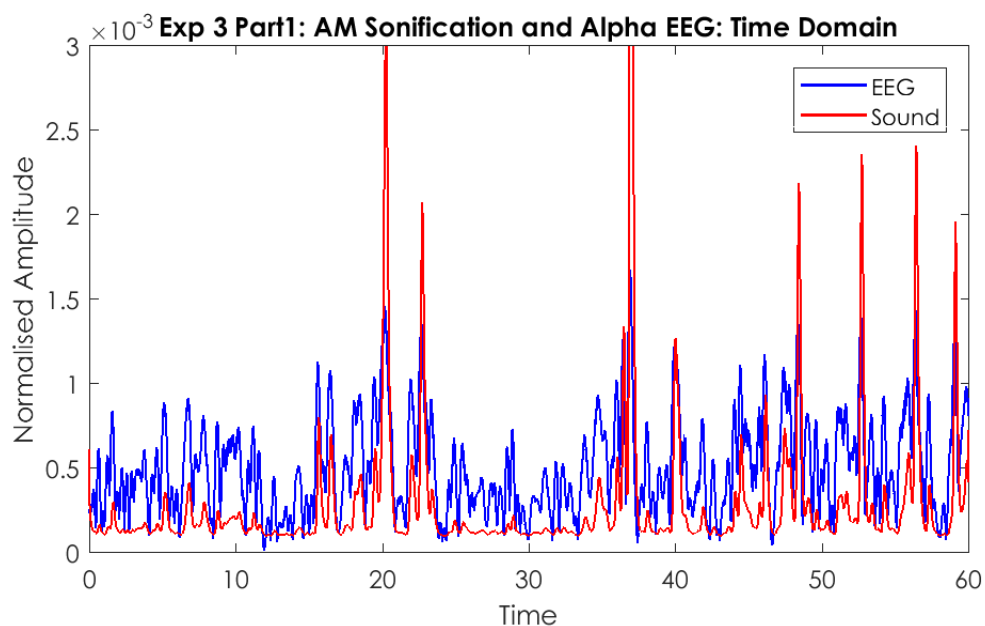
In [figure 6.2.2.2](#), it is more difficult to see the similarity between the EEG and its AM sonification. This is because of the exponential transfer function used in experiment 3, which visually accentuates the high amplitude components in the data and makes it difficult to see the lower amplitude components. However it can be seen that the peaks in the EEG do line up with the peaks in the sound.



**Figure 6.2.2.3:** Shows the Welch Power Spectral Density Estimate of the AM Sonification of F3.

In [figure 6.2.2.3](#), the peak of activity is at 261.6 Hz. However the second and third harmonics are much more prominent than in the previous AM sonification in experiment 1 and 2.

In [figure 6.2.2.4](#), the EEG and AM sonification have been overlaid on the same plot and the main peaks in the EEG activity can be seen in the sonification which proportionally has a higher amplitude. Thus the similarity at lower amplitude activity is more difficult to discern.



**Figure 6.2.2.4:** Shows the original EEG data in blue with the upper amplitude envelope of the AM sonification superimposed in red.

The maximum cross-correlation of the EEG with the AM sonification showed a slight time lag of 77ms. So when the Pearson correlation was computed at zero lag it gave only 0.594 but when the sonification was moved forward by 77 ms the correlation was 0.663 with a  $p < 0.001$ .

Clearly the exponential transfer function is producing a lower Pearson correlation of the AM sonification than in the previous experiments. But it should be remembered that the Pearson is a statistical comparison of the linear similarity of the two signals and caution should be taken when interpreting the cross-correlation for a nonlinear function.

Thus for the AM exponential transfer function the Spearman's rho correlation was calculated as it is appropriate for nonparametric data and for non-monotonic relationships (Howell, 2007, p276). Thus the Spearman's rho between the Alpha EEG and the upper amplitude envelope of the AM sonification, at a lag of 77 ms was 0.936 with a  $p < 0.001$ .

The next section will present a similar methodology for the FM sonification mapping.

### 6.2.3. FM Sonification and Frequency

The human auditory system's frequency response is generally given as a range from 20 to 20,000 Hz for a pure tone (Ward, 2010). However the ability to discriminate between frequencies tails off dramatically above 5,000 Hz (Wier et al., 1977). So for example a grand piano has a frequency range (in terms of fundamental notes) of 27.5 to 4186 Hz.

#### Just Noticeable Difference (JND-Hz)

Determining the just noticeable difference of frequency is not a trivial matter and there is a wide range of values given for the human JND-Hz. The **Weber** constant (or fractional increase above a baseline value that can be reliably detected) for frequency ( $k$ ) is given as between 0.003 to 0.667, depending on a wide range of factors like the speed of attack, the sustain or decay of the sound and even the method by which the subject makes the decision of a JND-Hz. (i.e. forced choice or ranked order). Again, with the inability to find an unequivocal and definitive JND-Hz, with a combination of the literature and experimentation, a JND-Hz of ( $\Delta f$ ) of 100 Cent or 5.613% was chosen with a base

frequency of 261.61 which is the note of C4, thus 40 JNDs take the maximum frequency to 2637.02 Hz which is E7.

At this point, it is useful to make use again of Hermann's recommended textual notation method for presenting the mapping function of a sonification in a human-readable method (Hermann et al., 2002, p39). Here is an example FM mapping in that notation:

### FM Sonification Transfer Function

**Alpha [0, 40] ( $\mu V^2$ ) – (exponential)  $\rightarrow$  Frequency [261.61, 2637.02] (Hz)**

This means that an input of the EEG alpha power in a range of 0 to 40  $\mu V^2$  (EEG power measured in micro-volts squared) is exponentially mapped to an audio frequency output of 261.6 Hz to 2637.02 Hz.

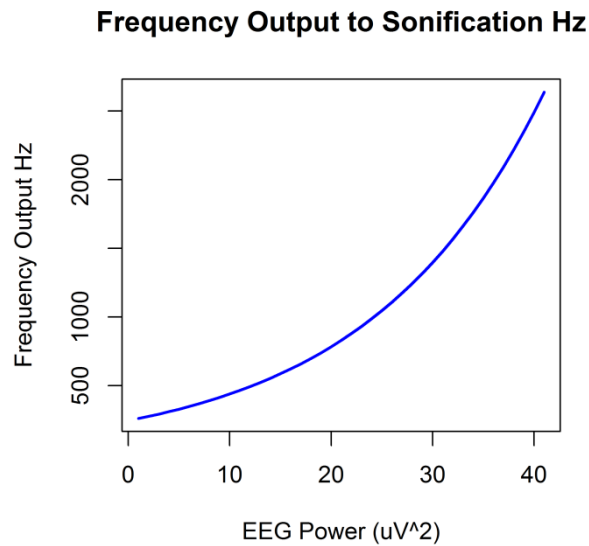
This mapping uses an exponential Transfer Function Equation for frequency which maps the varying power logarithmically into a range between a pre-chosen maximum and minimum frequency output as follows:

$$\text{Frequency} = 10.^{((\log(F_{\text{max}}) - \log(F_{\text{min}}) * \text{EEG}/\text{EEG}_{\text{max}} + \log(F_{\text{min}}))}$$

(Eq.6.2.3.1)

Where the  $F_{\text{min}} = 261.61$  and the  $F_{\text{max}} = 2637.02$  and EEG was the Alpha EEG input signal and  $\text{EEG}_{\text{max}}$  is the maximum amplitude of the EEG.





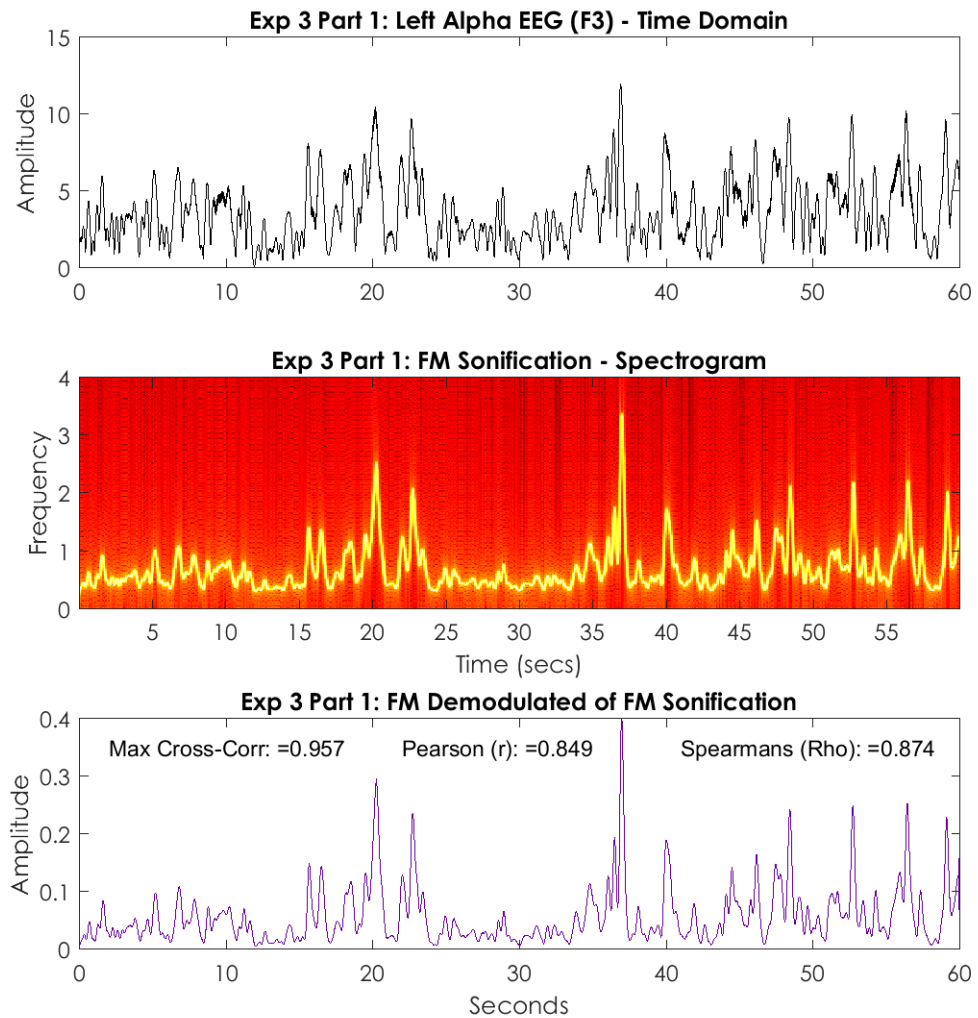
**Figure 6.2.3.1:** The blue line shows the exponential Transfer Function curve given by Eq.6.2.3.1 from EEG power input to the output of the FM sonification equation.

Thus for an Alpha EEG power input that ranges from 0 to 40  $\mu V^2$  (X-axis on the plot in [Figure 6.2.3.1](#)) will be perceived as a linear increase in frequency from 261.61 to 2637.02 Hz (Y-axis on the plot in [Figure 6.2.3.1](#)).

Therefore, in terms of available resolution and range (though not necessarily in other respects), these two sonification mapping functions should give a broadly perceptually equivalent' translation from the input of the Alpha EEG power to the sound output of the AM and FM sonification. This means they should have the same number of just noticeable differences across the output range making them in some sense perceptually equivalent.

The FM sonification used in the tracking trials (part 1) of experiment 3, is shown in [figure 6.2.3.2](#), with the time domain line plot of the EEG, the spectrogram and

FM demodulated signal (See: [4.2.2.2 FM Sonification](#) 161 page of details on demodulation)

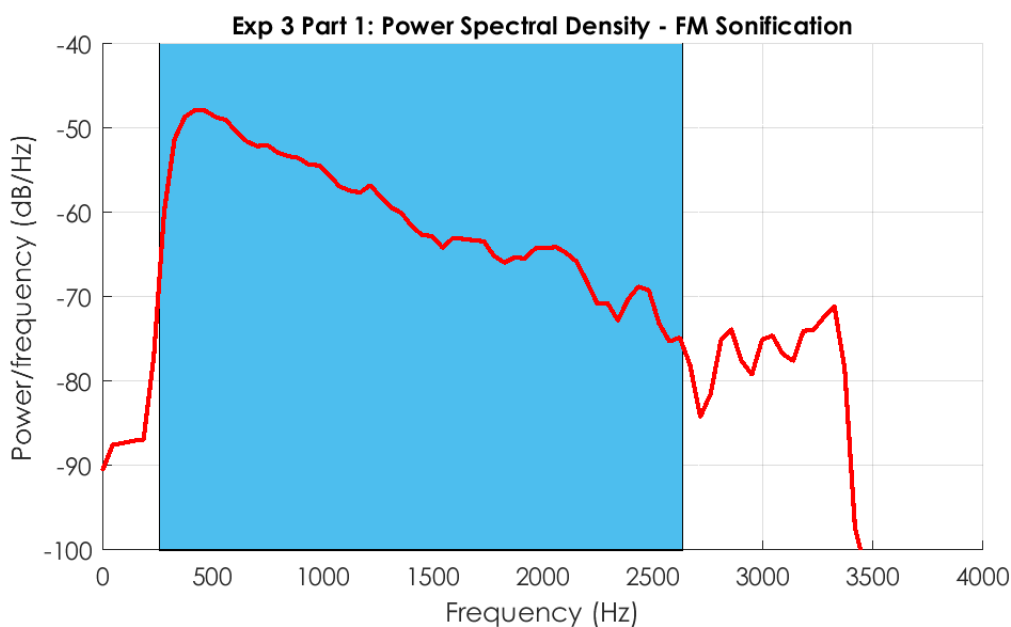


**Figure 6.2.3.2:** Shows the original EEG data use in the tracking task, in black, top subplot, the spectrogram (short-time Fourier transform) of the FM sonification with the 261.6 Hz modulation frequency in the middle and the FM demodulated signal in purpal on the bottom.

Similar to the AM sonification the exponential transfer function shown in [figure 6.2.3.2](#), has visually accentuated the higher amplitude data points in the EEG.

The Spearman's Rho has given a correlation of **0.874** at a  $p < 0.001$  between the Alpha EEG and the FM demodulated signal from the FM sonification.

In [figure 6.2.3.3](#), there appears to be some high frequency components in the sound, above the 2637.02 Hz upper cut off. These are possibly some harmonics and they are around 30dB lower than the main signal.



**Figure 6.2.3.3:** Shows the Welch Power Spectral Density Estimate of the FM Sonification from F3 with the 261.6 Hz modulation frequency. The blue box shows, the maximum output frequency range of the sonification equation of 261.6 to 2637.02.

As the same Alpha EEG data was used to generate both the AM and FM sonifications for the tracking task stimuli, it could be interesting to test how the extracted signals from each sonification method compare to each other.

The Spearman's Rho correlation between the upper amplitude envelope of the AM sonification and FM demodulation from the FM sonification was **0.982** at a

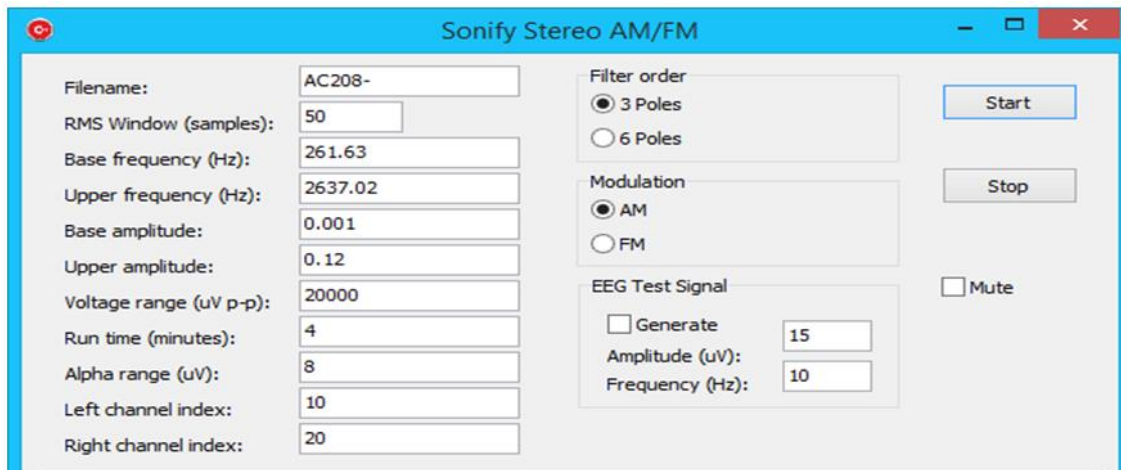
$p < 0.001$ . (The Pearson's  $r$  was 0.849 at  $p < 0.0001$ ). This provides some validation of both the enveloping and demodulation procedures used to analyse the sonifications.

Thus again it can be concluded that despite a reduction in the correlations in comparison to the first experiment because of the use of an exponential transfer function, the similarity between the original Alpha EEG data and their sonifications are sufficiently high to conclude that the EEG data used in the tracking task was adequately sonified.

#### **6.2.4. Sonification Software**

In the second part of experiment 3, the participants' own Alpha EEG was sonified in real-time using the same equations as above but this time with custom made software.

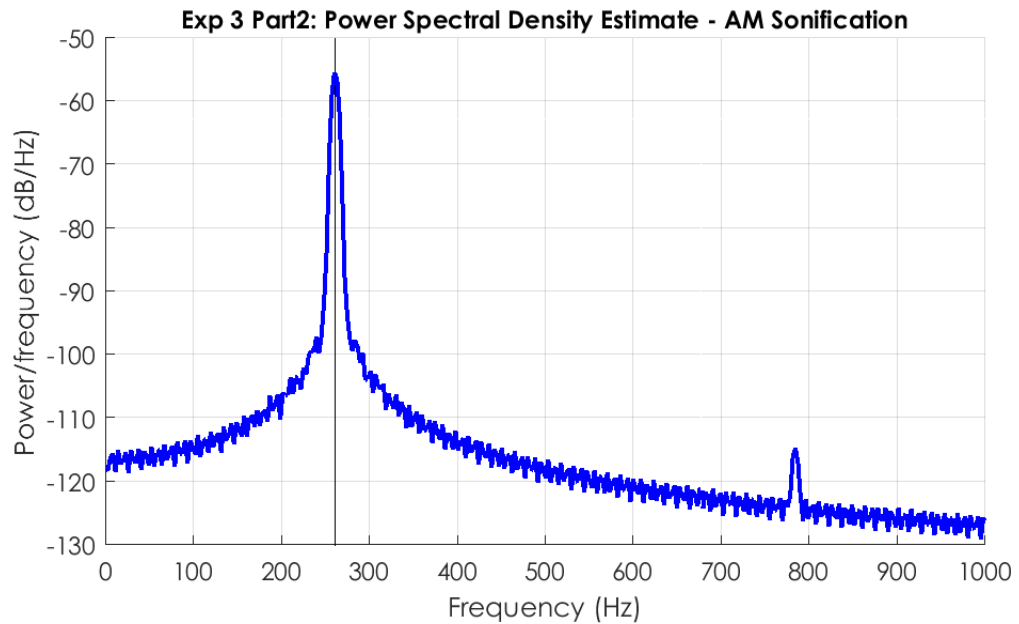
A number of options were explored with Matlab and Pure Data in order to communicate in real-time between the Mitsar EEG amplifier and the sonification software. In the end, custom sonification software was commissioned. The Mitsar-SDK provided the driver that sent raw EEG data to the custom sonification software. The software was written in C++ and [figure 6.2.4.1](#) shows the sonification software interface. The Mitsar amplifier has a sample rate of 500 Hz and the power was calculated over a 50 sample size RMS window (i.e. 100 ms). The filter was a 3<sup>rd</sup> order infinite impulse response (IIR) filter to extract the 8 to 12 Hz Alpha.



**Figure 6.2.4.1:** Custom Alpha EEG sonification software interface with AM and FM sonification settings. The bottom half of the display, which is missing in this figure, is where the EEG would be displayed.

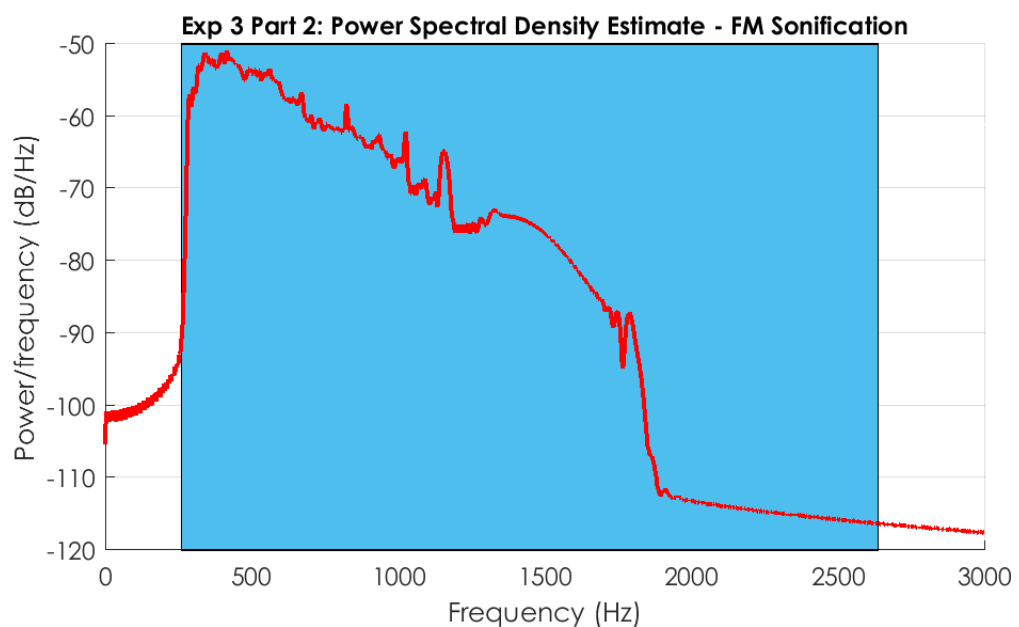
The sound output of the two sonifications from the custom software used in part 2 of experiment 3, were analysed with the same methods as above. The Spearman's Rho correlation for the AM sonification, between the Alpha EEG and the upper amplitude envelope of the AM sonification was **0.939** with  $p < 0.001$ . For the FM sonification the Spearman's Rho was **0.953** with  $p < 0.001$  for the correlation between the Alpha EEG and FM demodulation from the FM sonification.

Spectral analysis of the AM sonification from the custom software shows a cleaner frequency response than the version made for the tracking task, with no harmonics.



**Figure 6.2.4.2:** Shows the Welch Power Spectral Density Estimate of the AM Sonification F3 with the 261.6 Hz modulation frequency.

Similarly for the FM sonification shown in [figure 6.2.4.3](#) it can be seen that the output frequency range fits within the blue box of the expected frequency output. It should be noted that spectral plots are of the sonified EEG not a test signal, so a flat frequency response should not be expected in [figure 6.2.4.3](#).



**Figure 6.2.4.3:** Shows the Welch Power Spectral Density Estimate of the FM Sonification from F3 with the 261.6 Hz modulation frequency. The blue box shows, the maximum output frequency range of 261.6 to 2637.02.

Name	Pearson r	Pearson p-val	Spearman Rho	Spearman p-val
<b>AM Part1</b>	0.663	0	0.936	0
<b>FM Part1</b>	0.849	0	0.874	0
<b>AM Part 2</b>	0.679	0	0.939	0
<b>FM Part 2</b>	0.835	0	0.953	0

**Table 6.2.4.1:** Shows the correlations for both the AM and FM sonifications in both, part 1: the tracking trials and part 2: the neurofeedback training trials.

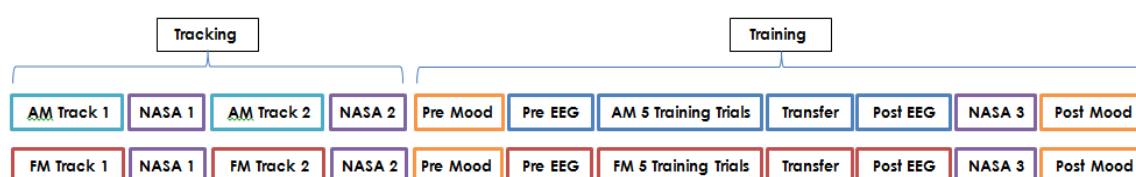
The correlations in table 6.2.4.1 are all very high and show that the Spearman's Rho gives higher scores than the Pearson's r. So again the software seems to have performed adequately in translating the EEG data into sound.

### 6.3. Experiment Design

Experiment 3 entailed two sessions of approximately one hour duration, a week or more apart, at roughly the same time of day. In order to try to control for the circadian rhythm, which is the roughly 24 hour cycle of many systems in the body, and which can have a large effect on the Alpha EEG measures, the sessions were scheduled to have a maximum of plus or minus one hour difference in time of day. The mean time difference between the two sessions was 26 minutes, although because of availability problems, one participant had

1:54 hours and another had 1:39 hours difference in time of day between the sessions.

As shown in [figure 6.3.1.1](#), each session consisted, in random order, of either the AM or FM sonification. Within each session, participants did two types of tracking task for one minute each, followed by Alpha EEG sonification neurofeedback for 20 minutes. After each tracking trial and the training task, the NASA Task load Index (NASA-TLX) questionnaire was given and the nine-question mood survey was administered pre and post of the training task.



**Figure 6.3.1.1:** Experiment 3 design: Two sessions with AM or FM in a random order, with Tracking followed by Training trials. The 'Track 1' and 'Track 2' trial was either a 'Panning' or 'Vertical' tracking task, again in random order. The Training section consisted of eight trials of four minutes each, a 'Pre EEG' baseline, five training trials, a 'Transfer' trial and a 'Post EEG' trial.

This is a mixed design with order as a "between subjects" factor, where 9 participants started with the AM sonification and 8 did the FM first. The "within subjects" measure is the NASA-TLX which was taken at three time points, after each of the two tracking tasks and after the training task and the mood questionnaire that was taken before and after the training trials. There were also the accuracy scores of the two different tracking tasks and EEG measures of the 8 trials of four minutes each in the training trials, i.e. Pre-EEG, 5 training, 1 transfer and the Post EEG (as described below).



### 6.3.1. Session

Each session took around one hour and consisted of 19 components. First the experiment was explained to the participants and the exclusion criteria checked and then the consent form was signed. Participants then carried out the two tracking trials in a random order (see [6.5.1](#) for Tracking Instructions). After each tracking trial participants filled in the 6 questions of the NASA-TLX. Prior to the training trials they filled in the 9 questions of the Pre Mood questionnaire. Then the electrodes were placed on the participant's head and the impedances were checked to be below 5 kilo ohm (This is a measure for the quality of the connection). Then the two channels of real-time raw EEG were shown to participants and they were asked to blink and bite to demonstrate typical non-EEG artifacts. They were then given some time to play with the signal to learn what gave a good and bad signal. Then a 1 minute EEG recording was taken with eyes closed, using the commercial WinEEG software in order to estimate the individual maximum alpha amplitude to scale the sonification, see [section 6.2.2](#) above.

Then, as shown in [table 6.3.1.2](#) below, the real-time EEG section consisted of eight trials of 4 minutes all with eyes closed and a break between each to scratch, stretch and blink. The first Pre-Baseline EEG was recorded with no feedback sound and the participants were instructed to sit quietly and relax. Then there were 5 training trials (See [section 6.5.2](#) Measures 2: EEG for details), followed by a '**Transfer**' trial where the person was instructed to keep training as they had been in the 5 training trials but this time without any sound feedback. If participants were able to show a change in EEG in the Transfer trial, this would be a strong indication of volitional control of the EEG and learning. Finally there

was a 'Post' training EEG, where the EEG was recorded but the participant was instructed not to do any training. This was followed by the Post NASA-TLX and Post Mood questionnaires. After the second session, participants were given an opportunity to ask questions and the details of the experiment were explained. In total, participants did 20 minutes of EEG sonification neurofeedback and spent around 35 minutes with the EEG cap on. A total of 37 sessions were conducted over 19 days.

<b>Experiment 3: Session</b>	<b>Time (mins)</b>
1. Instructions	3
2. Consent	2
3. Practice	2
4. Tracking 1	2
5. Post Track 1 – NASA 1	2
6. Tracking 2	2
7. Post Track 2 – NASA 2	2
8. Pre Train - Mood questionnaire	2
9. EEG Hook-Up & Demo	3
T1. Pre-Baseline EEG	4
T2. Sonification Training 1	4
T3. Sonification Training 2	4
T4. Sonification Training 3	4
T5. Sonification Training 4	4
T6. Sonification Training 5	4
T7. Transfer Trial (NO-feedback)	4
T8. Post Train - EEG	4
18. Post Train - NASA 3	2
19. Post Train - Mood	2
Session Duration	<b>56</b>

**Table 6.3.1.2:** Shows the order and duration of the components of the experiment.

### 6.3.2. Sample Size and Power Estimates

Because many EEG sonification studies fail to report power, let alone estimates of effect size, it was difficult to find any useful data in the literature to compute power and estimate sample size for electrode positioning relevant to frontal alpha asymmetry, (F3 and F4 in reference to Cz: top centre of the head).

So the first simple step was to compute the average sample size of the 11 studies that had done sound-based Alpha EEG neurofeedback training. With a total of 262 participants, the average training group size was **15**, with a range of 8 to 50. Most studies did not have control groups but often had several intervention groups.

However, there was a complication in making this computation, since, despite the author having recorded hundreds of EEGs over the last 15 years, all the EEGs have been recorded in the standard 'linked ears referential montage' up until now. Potentially this set up is not optimal for measuring frontal alpha asymmetry, as EEG is a measure of electrical flows that are mostly perpendicular to the scalp and the dipole (the maximal positive and negative electrical flow of the field potentials) of left and right frontal cortex is located in gyral surfaces (Srinivasan et al., 2006) which points tangentially to the ears. Thus the linked ears referential montage may not adequately capture frontal alpha asymmetry activity. This suggests that the reference electrode for the frontal alpha asymmetry measure should be placed at Cz (Allen, Urry, et al., 2004) as this should better capture the frontal alpha asymmetry activity.

Therefore the EEG data from 30 participants from two previous experiments was re-montaged to an "Average weighted montage" (AvW) (estimating the

Laplacian operator for each electrode using Lemos's modified method)). Using this arrangement, mean power and standard deviation were computed. Although this will not give exactly the same results as a recording with a Cz reference, it is hoped that it will be a good enough estimate in order to calculate power and estimate sample size. The results found the mean was 2.68  $\mu V^2$  and the standard deviation was 2.50  $\mu V^2$  for the group of 30 subjects.

Using the 'RStudio'<sup>5</sup> statistics environment (RStudio, 2015) the '*power.t.test()*' function was computed for a one-tail 't test power' calculation with alpha level of 0.05 and an estimated difference between groups equivalent to the standard deviation of 2.50.

For a significance level = 0.05 (Alpha level) the sample size needed is  $N = 12.32$  (i.e. = 13), with a power of = 0.959 (recomputed for  $N = 13$ ).

For a significance level of = 0.01 the sample size would have to be  $N = 18.61$  (i.e. = 19). This would give a power = 0.954 (recomputed for  $N = 19$ ).

Thus the critical level for a sample size is an  $N = 13$  and gives a 1-tail t-distribution with an alpha of 0.05 of 1.782, therefore with a mean from previous data of 2.68 the upper bound of the confidence interval is 3.94. i.e. Null Hypothesis is  $H_0: \mu = 2.68 \pm 0.89$  and Alternative Hypothesis is  $H_1: \mu > 3.94$ .

Additionally there would be no need to get more than 30 participants per group, as with a significance level of = 0.01, and a group size of  $N = 30$ , this gives a power of 0.998 and as 1 is the maximum, this will not change much as the group gets bigger than 30.

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<sup>5</sup> RStudio is an open source data analysis software (RStudio, 2015)

Thus in summary, the previous experiments have an average group size of **15** participants and the power calculations estimate there should be a minimum group size of **13** participants for an Alpha level of 0.05 and a group size of **19** participants to achieve an Alpha level of 0.01. However this experiment is using a cross-over design therefore it would be desirable to have an equal number of participants in each group to balance the groups. Therefore a target of 20 participants was chosen and a minimum of 16 was set, as this would allow drop-outs or corrupted data of a few participants without losing the statistical power in the experiment.

### **6.3.3. Block Randomisation**

To randomise the order that the participants did the AM or FM sonification trials, the '*block.random()*' function in RStudio was used to create a two block random lists of 30 participants. The block randomisation method was chosen as it keeps the groups balanced throughout the duration of the experiment. Thus if time ran out before the required number had been collected, or if recruitment was better than expected and more participants did the experiment, the groups would still be balanced. The random ordering of the tracking trials and the NASA-TLX and Mood questionnaires were computed at run time using the PsychoPy software.

### **6.3.4. Participants**

Twenty participants were recruited into the experiment and completed at least one session. Three participants dropped out. One reported having a headache after the session and although it was felt unlikely to be due to the training, he was a very sensitive person and was nervous to do a second session, so some

conventional relaxation neurofeedback sessions were given instead. Another person felt anxious after the session and as she had a dissertation deadline looming. It was agreed she would withdraw. After the first session the third person took exception to the idea of his data being published. The seventeen participants that completed both sessions had a mean age of 44 years and an age range from 26 to 70. Eight were female and nine male.

#### **6.3.5. Exclusion Criteria**

Participants had to be over 18 years old, and were only recruited if they did not have any problem with their hearing, as this is a listening experiment. Also they should not have had a history of convulsive disorders, epilepsy or other seizures as this could potentially be exacerbated by neurofeedback (although this is unlikely with an alpha enhance protocol). Also excluded was any major head injury with loss of consciousness as this can affect the EEG recording. Participants should not have taken any psychoactive drug, either prescription or recreational, for two days prior to the experiment, since most psychoactive medication will change EEG patterns. Participants were instructed not to stop any medication in order to take part in the experiment.

#### **6.3.6. Ethics**

The general purpose and design of the experiment was explained to the participants and they were informed that their personal data would be kept confidential and all data analysis and publications will be based on anonymised data. Participants were made aware both in discussion and in the information sheet, before signing the consent form, of their right to withdraw

from the experiment at any time without having to give a reason and their data would be destroyed.

Participants were informed that if they tick the consent box on the form, their anonymised digital questionnaire, tracking and EEG data would be permanently deposited on a publicly open database, in order to help further EEG sonification research. They could also tick a consent box to receive a summary report of the research findings.

At the end of the data collection sessions participants were given the opportunity to discuss any issues they may have from the experiment.

As a PhD experiment, it was not practical to work with a clinical population such as those suffering from depression, therefore only healthy adults over 18 years of age were recruited.

The experiment received ethics approval from the Open University Human Research Ethics Committee number HREC/2015/2011/Steffert/2 and was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2000).

### **6.3.7. Hardware**

In order to address various problems identified in previous experiments, several changes were made to the hardware used for the experiment, as detailed below.

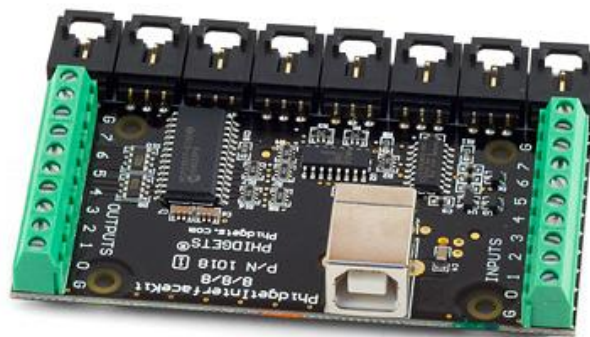
#### **6.3.7.1. Slider Box for Tracking Task**

In order to address a problem identified in experiment 1, a dedicated physical slider (as opposed to a mouse) was developed for the tracking task. In the

tracking task in experiment 1, participants were asked to click on a screen based slider and manipulate it with a computer mouse. The tracking accuracy scores had been lower than expected, and lower than scores obtained in the piloting process, so given how quickly the sound of the EEG signal fluctuates, clearly some users, particularly the older ones not used to using a computer, had some difficulty in manipulating the slider with a mouse so rapidly.

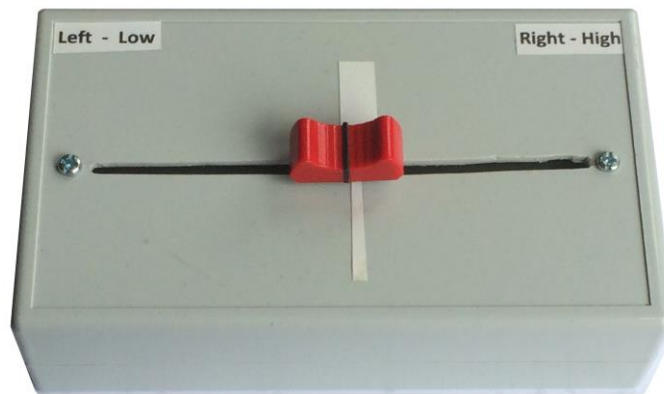
Encouragingly, Zaccaria (Zaccaria, 2011) used a design with a dedicated physical slider to assess an EEG sonification and obtained much better tracking accuracy scores than obtained in experiment 1. This may in part be explained by the use of a physical slider, although the Zaccaria study used much shorter sound clips of 10-15 seconds and appears to have had greater temporal averaging of the EEG signal, although this was not clearly specified.

A custom slider box ([figure 6.3.7.1.2](#)) was made with a Phidgets Interface Kit 8/8/8 sensor board ([figure 6.3.7.1.1](#)) and 100 K ohms slide potentiometer, fixed inside a standard project box with a USB connection to the laptop. The Phidgets used a Pyserial driver to interface with the PsychPy software in Python.



**Figure 6.3.7.1.1:** Phidgets Interface Kit 8/8/8 sensor board.





**Figure 6.3.7.1.2:** Custom made slider for tracking task using a Phidgets Board. Labels were placed on each end of the box with “Left – Low” on the left and “Right – High” on the other.

### 6.3.7.2. EEG amplifier

In experiment 2, the Muse headset, a consumer grade EEG device that outputs OSC data was used.

In this third experiment, custom sonification software was commissioned in order to be able to communicate directly in real-time with the medical grade Mitsar EEG amplifier ([figure 6.3.7.2](#)). This allowed for a more rigorous specification of filter settings and better control of data package timings, as well as the use of conventional gelled electrodes on F3 and F4 scalp locations and a Cz reference for the asymmetry measure. (This is not possible with the Muse headset, which can only record EEG from the forehead and temporal lobes in reference to Fpz).

The Mitsar 202 amplifier (Mitsar Co. Ltd.), was used to record the EEG files for the tracking task and all the training sessions. The Mitsar has 24 channels at a sample rate of 2000 Hz at 24 bits, which is output at 500 Hz with a frequency range of 0 Hz up to 150 Hz and noise level of < 1.5  $\mu$ V peak to peak. The Mitsar is

a CE certified medical device (See appendix [A3.4](#) for 'Directive 93/42/EEC' certificate and datasheets).



**Figure 6.3.7.2:** Mitsar 202 EEG amplifier.

### 6.3.7.3. Sound Card

In order to ensure the quality of the audio output from the laptop and to play the sonifications at an audio sample rate of 48,000 Hz, an **Aureon XFIRE8.0HD** USB external Sound Card (Terratec) was used. Several sound cards were tested and the Aureon XFIRE8.0HD was eventually chosen because of its ergonomic volume knob ([Figure 6.3.7.3](#)). The Aureon XFIRE8.0HD was placed within easy reach on the edge of the table which allowed participants to easily adjust the volume without having to look at the computer or even open their eyes.



**Figure 6.3.7.3:** Aureon XFIRE8.0HD USB external Sound Card

#### 6.4. Data Processing and Analysis

In experiment 3, four measures were analysed, the **Tracking data**, the **Alpha EEG** from the 8 training trials, the **NASA-TLX Task Load Index** and **Mood** questionnaire. There were four hypotheses to be tested, as follows.

**The Null hypothesis H0:** There will be no statistical change at the  $p > 0.05$  level in EEG frontal Alpha brain wave at F3 or F4 or mood in any of the outcome measures as well as no differentiation between the two types of sonification on tracking accuracy or NASA-TLX task load measures.

**H1:** Adults who are naive to neurofeedback will be able to increase their own frontal EEG Alpha activity on the right (F4) and/or decrease it on the left (F3) by hearing a real-time sonification of their EEG Alpha activity.

**H2:** Self-rated scores of 'Excitement' will increase and/or levels of 'Tension' will decrease.

**H3:** There will be a difference between the two types of sonification on tracking accuracy or task load measures.

**H4:** There will be a positive correlation between **Tracking** accuracy and levels of Alpha activity in the **Training** trials.

The statistical analyses were performed with SPSS (IBM Corp. Released, 2015). For the T-Tests the effect sizes were estimated by Cohen's (d) (Cohen, 1969) and for the ANOVAs the partial eta square ( $\eta^2$ ) is reported. The Alpha level was set at 0.05 (two-tailed) for all statistical tests and Greenhouse-Geisser correction was used to correct for unequal variances where necessary.

#### 6.4.1. Measures 1: Tracking

The presentation of two concurrent audio streams will have quite different acoustic and perceptual subjective characteristics between AM and FM sonifications. So for example, as the amplitude of the AM sonification wax and wane on the left and right sides, it is likely to be perceived as a horizontal panning from left to right, whereas changes in frequency in the FM sonification will not.

In the preliminary testing for this third experiment it was found hard to formulate tracking instructions that encompassed both sonification techniques that were clear, but which did not implicitly favour one sonification over the other. For example, explicit instructions to track the panning of the sound were very clear for the AM sonification, but did not apply at all to the FM sonification. By contrast, instructions to track the height or intensity of both ears favoured the FM sonification. Interestingly, the first approach emphasised a description in terms of the difference of the two audio streams, whereas the second emphasised a description in terms of the sum of the two audio streams.

For this reason it was decided to suit the instructions in this experiment to the sonification, as detailed below. The two different instructions can be seen symbolically as either, horizontal tracking for the panning instructions and vertical tracking for the summing instructions. The direction of the slider was set accordingly for the different trials.

The tracking task consisted of two trials per session, presented in a random order, so four trials for each person for the two different sonifications. In the 'Panning' trial a physical slider was placed horizontally in front of the

participants and they were instructed to try and track the activity of the two sounds from left to right. In the other trial, the slider was placed vertically and the participants had to track the 'sum' of the two sounds up and down. The Tracking Instructions were as follows:

#### **Amplitude Modulation Instructions:**

*"Please now listen to a one minute sound file, two times. You will hear two sounds, one in each ear and the **volume** of the sounds will change. There will be two different tracking tasks (in a random order) where you must try and track the activity of the sound using a slider.*

*One task is to track the activity of the sound as it moves from left to right. So as the **volume** increases on the right side or decreases on the left side, you move the slider to the right and vice versa.*

*In the other task you must track the overall **volume** of both sounds together. So as the **volume** of both sounds increases, you move the slider up and as they decrease you move the slider down. If the **volume** of one side goes up and the other goes down, you must try and decide whether the average of both is increasing or decreasing.*

*Try and follow the activity as quickly and as accurately as possible".*

#### **Frequency Modulation Instructions:**

*"Please now listen to a one minute sound file, two times. You will hear two sounds, one in each ear and the frequency of the sounds will change. You have two different tracking tasks (in a random order) where you must try and track the activity of the sound using a slider.*

*One task is to track the activity of the sound as it moves from left to right. So as the **frequency** increases on the right side or decreases on the left side, you move the slider to the right and vice versa.*

*In the other task you must track the overall **frequency** of both sounds together. So as the **frequency** of both sounds increases, you move the slider up and as they decrease you move the slider down. If the **frequency** of one side goes up and the other goes down, you must try and decide whether the average of both is increasing or decreasing.*

*Try and follow the activity as quickly and as accurately as possible".*

After the participants read the instructions, the experimenter then reiterated the objectives of the task and answered any questions. Participants were then given a chance to practice each tracking task prior to each one minute tracking trial.

Although most people seem to find the instructions quite clear and were confident about what they were expected to do, some participants did initially have difficulty grasping what was required, so more practice and explanations were given. Also there was considerable variation in how some participants interpreted the instructions. Some people moved the slider very slowly but when questioned insisted they were tracking the activity that they could hear. Conducting two different types of tracking tasks (i.e. both horizontal and vertical) in the same session did not appear to present a problem for the participants.

Intriguingly some people reported that after tracking the sound for a little time they had the perception that they were creating the changes in the sound, rather than just tracking it.

#### **6.4.1.1. Stimulus Presentation**

The sound stimulus and all the questionnaires were presented using PsychoPy, a free open source stimulus presentation software (Peirce, 2009). The trials followed a similar format to experiment 1. After reading the instructions and a practice trial the participants would click on a button to go to the tracking screen. There was then a 3 second pause before the sonification started to play, in order to allow the participants to prepare. As they moved the physical slider in front of them, a horizontal slider on the screen would mimic the activity and display the score which ranged from 1 on the left to 1000 on the right (See, [figure 4.3.4](#) in [chapter 4](#), for example slider screen). When the one minute sound finished playing the software would automatically switch to the NASA-TLX questions. Once the participants had finished filling in the questionnaire, they were given the opportunity to take a break before clicking to do the second tracking trial.

Participants wore a set of headphones and were sat alone with the experimenter in a quiet room. Many people chose to close their eyes during the tracking task, although they were not explicitly instructed to do so.

#### 6.4.1.2. Data Processing

In order to assess the tracking accuracy of the four different trials, the tracking data was compared to 6 different indices. (For clarity these will be labeled “Index 1” to “Index 6”)

**Indices 1 & 2:** In the literature there are two main ways to compute the Frontal Alpha Asymmetry ratio between left and right frontal alpha EEG. Allen et. al, computed it as;  $FAA = (F3 - F4) / (F3 + F4)$  (Index 1), for each data point in the time-series (Allen, Harmon-Jones and James H. Cavender, 2001).

Whereas the second asymmetry measure (Index 2), uses the natural log of the right EEG minus the natural log of the left;  $LogFAA = LN(F4) - LN(F3)$  (Stewart et al., 2014; Allen, Harmon-Jones and James H. Cavender, 2001).

**Indices 3 & 4:** However, because people are presented with the two left and right channels individually, they may choose to track only one of the sound streams. Therefore the tracking data will be compare to the alpha EEG from the left F3 (Index 3) and right F4 (Index 4) individually.

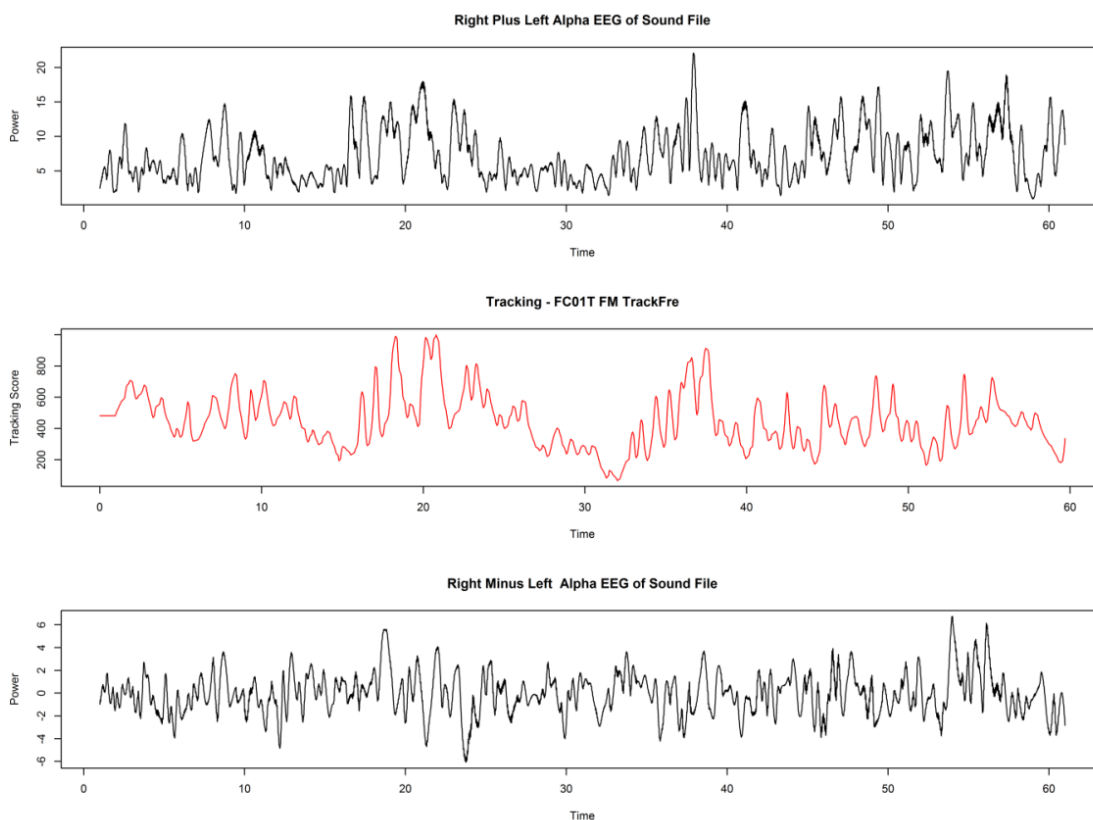
**Indices 5 & 6:** Lastly, as the instructions in the panning trial required the participants to track the difference between left and right it was thought comparing the tracking data with a measure of the difference in the EEG, between F4 and F3 may give a better comparison as this is closer to the objectives of the Panning tracking trial, than the raw left and right Alpha channels or the asymmetry. Thus Index 5 is calculated as Right Minus Left;  $RML = \text{right F4} - \text{left F3}$ . Analogously, for the vertical tracking trial, participants were instructed to track the sum of the two channels. Consequently, Index 6 is a



measure of Right Plus Left; RPL = right F4 plus left F3 and was computed for each data point in the time series.

The tracking task was administered in the PsychoPy software and every time the slider moved a data point was logged, this was linearly interpolated to 500 Hz in order to match the EEG sample rate. This is the red line in [figure 6.4.1.2.1](#) below.

- Thus:
- Index 1:**  $FAA = (F4 - F3) / (F4 + F3)$
  - Index 2:**  $LogFAA = \ln(F4) - \ln(F3)$
  - Index 3:**  $F3$
  - Index 4:**  $F4$
  - Index 5:**  $RML = F4 - F3$  (Right Minus Left)
  - Index 6:**  $RPL = F4 + F3$  (Right Plus Left)



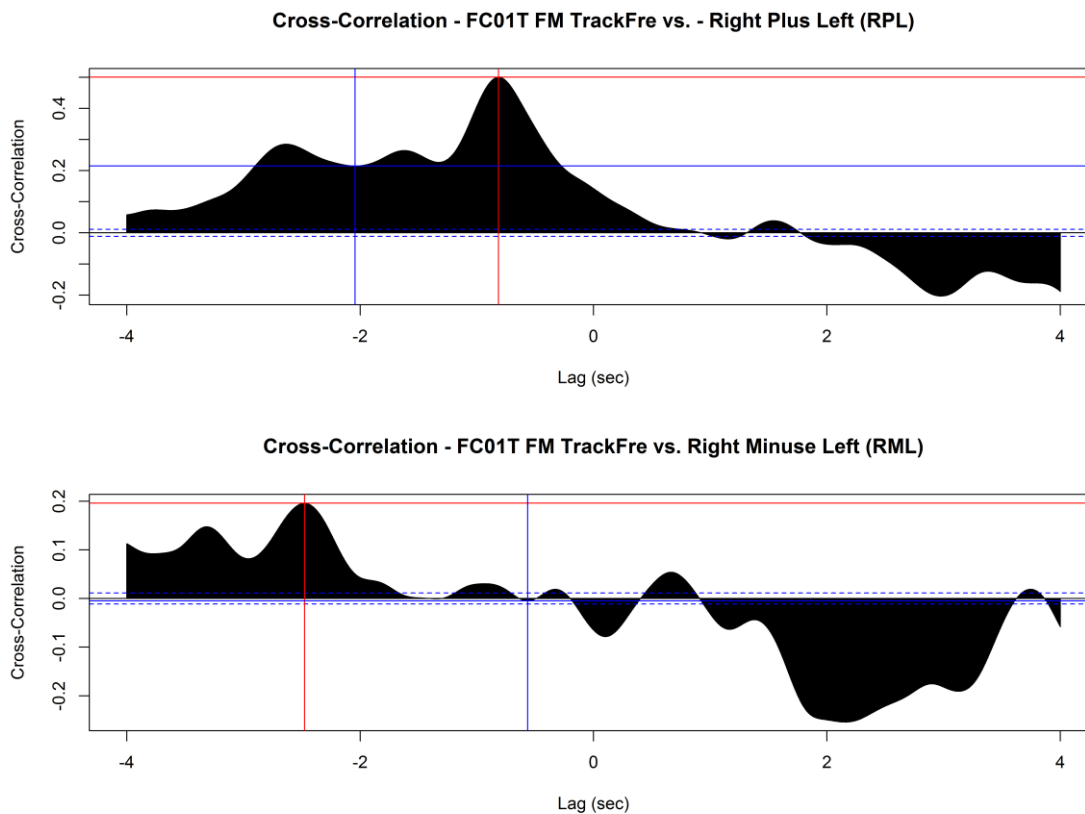
**Figure 6.4.1.2.1:** An example of good tracking data. The top trace is of the 'right plus left' (RPL) time series Alpha EEG, The middle trace in red is of the slider response data of participant listening to the FM sonification with the instructions to track the sum of the activity (Vertical). The bottom trace is of the 'Right Minus Left' (RML) Alpha EEG.

### 6.4.1.3. Tracking Correlate

The Cross Correlation Functions (CCF) for all 68 tracking trials from all participants and all six indices was computed in R Studio and plotted to determine the best measures to choose for the tracking scores. (See Appendix [A5.3](#) for summary statistics of the CCF measures and plots and Appendix [A6.5](#) for R script)

The Cross Correlation is a convolution function that computes the Pearson correlation between the EEG time-series indices and the tracking data at time point one and then moves the tracking data back one data point (2ms) and then re-computes the correlation. The output is a series of correlations that has a maximum (**Max**) and minimum (**Min**) correlation, as well as a time Lag from the start of the file to the maximum (**MaxLag**) and to the minimum correlation (**MinLag**). Given that the average reaction time for a simple button push is in the order of 200 to 300 ms, it was assumed that correlations quicker than 300 ms would be guess work and after 2.5 seconds the person was not following the sound and the correlations would be just noise and this was confirmed by examining all of the CCF plots. Therefore all maximum and minimum correlations were restricted to a time window of -300 ms to -2.5 seconds.

As shown in [Figure 6.4.1.2](#), the cross correlation are plotted for plus to minus 4 seconds but only correlations in a time window of -300 ms to -2.5 seconds are taken as acceptable. The red line shows the maximum CCF and the blue is the minimum CCF. In this example the cross correlation is highest for the **RPL** with a maximum CCF of 0.494 but only 0.098 for **RML**.



**Figure 6.4.1.2:** Plot of the Cross Correlation Functions for the same tracking trial data as figure 6.4.1.1. The top plot is the CCF of the tracking data with 'Right Plus Left' Alpha EEG data (RPL). The bottom plot is of the tracking data with 'Right Minus Left' Alpha EEG data (RML).

#### 6.4.1.4. Cross Correlation Functions: Polarity

Because the participants were tracking two separate sound sources simultaneously, one in each ear, and this can be a demanding task, it is possible that some people tended to listen to the left-hand sonification more and others to the right-hand. It is also possible that some people interpreted the tracking task differently and tracked in the opposite direction. Therefore the largest correlation could be a negative correlation.

Therefore, two further indices were computed from the maximum and minimum Cross Correlation Functions. The first measure is the value of the maximum correlations regardless of whether it is positive or negative for each index for each person this will be called the 'absolute maximum CCF'.

The second is a simple count of whether the maximum correlations were positive or negative for each Index; see [table 6.4.1.3](#), in order to see if the minimum CCF may be more appropriate than the maximum CCF for any of the six measures.

Count %	F3	F4	FAA	Log-FAA	RML	RPL	Sum
AM Pan	65%	82%	82%	88%	88%	71%	79%
AM Vertical	82%	88%	65%	65%	76%	82%	76%
FM Pan	59%	71%	94%	94%	100%	53%	78%
FM Vertical	94%	100%	100%	100%	88%	100%	97%

**Table 6.4.1.3:** Shows the percentage of trials out of 17 that the maximum CCF is greater than the minimum CCF i.e. how often the positive correlation is greater than the negative correlation, for all six indices and the sum of all six (Sum).

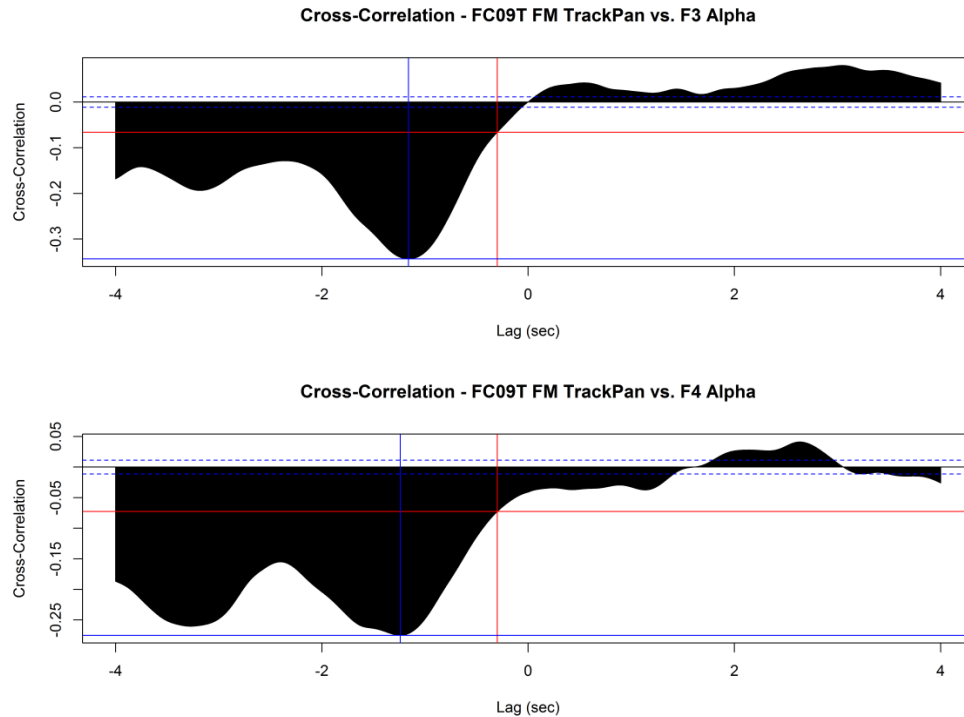
In the **FM Vertical** trials in [table 6.4.13](#), only 3 out of the 102 measures. (i.e. 17 participants multiplied by the six indices) had an absolute minimum CCF greater than their absolute maximum CCF, one person for F3 and two for RML but both scores were all very low, so it was probably just the 'noise' from poor tracking not a '**Negative Polarity**' of the person tracking in the opposite direction.

Furthermore the **Mean** of the Max-CCF for the **FM Vertical** trials for all 17 participants of **F3** was **0.338** but the Mean of Min-CCF was only **0.083**. For **F4** the Max-CCF = **0.366** and Min-CCF = **0.142**. Thus for the FM Vertical trials it can be concluded that everyone interpreted the instruction as intended and as the frequency increased on the left or right they moved the slider up.

But as can be seen in [table 6.4.1.3](#) for the other 3 tracking trials this is not the case, so for example in the 'FM Pan' trials for **F3** only **59%** of the measures have the Max-CCF greater than the Min-CCF and **F4** was **71%**. For 'AM Vertical' trials, F3 was **82%** and F4 was **88%** and for the 'AM Pan' trials F3 was **65%** for and F4 was **82%**.

### Example of Negative Cross Correlation

An example is shown in [figure 6.4.1.4](#); where participant 'number nine' got a maximum CCF score of just **-0.066** between the tracking and F3 but the minimum CCF score was **-0.343**. Clearly **-0.343** is not just 'noise' of bad tracking but participant 'number nine' must have lowered the slider as the frequency of the sonification increased and vice versa, this would be a '**Negative Polarity**'.



**Figure 6.4.1.4:** Plot of the Cross Correlation Functions of the tracking trial with F3 (Top Plot) and F4 (Bottom Plot) for the FM Pan tracking trial. All scores are negative and the absolute minimum is greater than the absolute maximum,

**Table 6.4.1.5** below shows the Cross Correlation scores for participant 'number nine' and only the 'FM Pan' trial, shows the reverse polarity, where in F3, F4 and RPL the minimum CCF is larger than the maximum CCF.

Maximum and Minimum Cross Correlation for Participant: 9								
	F3		F4		RML		RPL	
	Max	Min	Max	Min	Max	Min	Max	Min
AM Pan	0.183*	-0.016	0.198*	0.102	0.165	-0.029	0.188*	0.054
AM Vertical	0.294*	0.149	0.323*	0.157	0.069	0.007	0.342*	0.170
FM Pan	-0.066	-0.343*	0.073	-0.275*	0.092	-0.057	-0.077	-0.342*
FM Vertical	0.460*	0.186	0.407*	0.228	0.130	-0.079	0.480*	0.251

**Table 6.4.1.5:** Shows the Cross Correlation score for participant 'number nine'. F3 is left Alpha EEG and F4 right, 'Right Minus Left' (RML) and 'Right Plus Left' (RPL). Note how F3, F4 and RPL the 'Max' has the higher scores except for the

'FM Pan' trial were the 'Min' is higher than the Max (highest score in red text and asterisks) also note RML has very low scores overall.

#### 6.4.1.5. Absolute Maximum Cross Correlation Functions

For the majority of CCF's the mean of the Max-CCF is an order of magnitude greater than the mean of the Min-CCF. But, as highlighted in red in [table 6.4.1.6](#), the biggest maximums vary across different measures for each of the four tracking tasks. RPL has the highest CCF with both AM-Ver and FM-Ver, but F4 wins for FM-Pan and RML for AM-Pan.

Group Mean (Max CCF) for all 17 people						
	F3	F4	FAA	Log-FAA	RML	RPL
AM Pan	0.168	0.207	0.140	0.133	0.217*	0.197
AM Vertical	0.297	0.329	0.072	0.071	0.104	0.341*
FM Pan	0.142	0.189*	0.137	0.131	0.186	0.163
FM Vertical	0.338	0.366	0.137	0.136	0.147	0.389*
Group Mean (Min CCF) for all 17 people						
	F3	F4	FAA	Log-FAA	RML	RPL
AM Pan	-0.094	-0.003	-0.035	-0.036	-0.030	-0.040
AM Vertical	0.053	0.070	-0.036	-0.033	-0.038	0.072
FM Pan	-0.089	0.003	-0.024	-0.025	-0.017	-0.037
FM Vertical	0.083	0.142	-0.019	-0.016	-0.030	0.134

**Table 6.4.1.6:** The top half is the means of the 'Maximum Cross Correlation Functions' for each of the 6 different indices. The bottom half is of the means of the 'Minimum Cross Correlation Functions'. The indices are: Right frontal alpha EEG (F3), Left frontal alpha (F4), Frontal Alpha Asymmetry (FAA), Log Frontal Alpha Asymmetry (Log-FAA), The right frontal alpha minus the Left (RML), The right plus the Left (RPL).

But, as can be seen in [table 6.4.1.5](#) above, from participant 'number nine' just taking the mean of all the Maximum **or** Minimum Cross Correlation Functions, fails to take into account any trials with a reverse polarity. Therefore [table 6.4.1.7](#) shows the **absolute maximum** of the Maximums or Minimums for each participant.

Mean of the Absolute Max if the (Max CCF) and (Min CCF) for all 17 people						
	F3	F4	FAA	Log-FAA	RML	RPL
AM Pan	0.239	0.243	0.147	0.140	0.220	<b>0.245</b>
AM Ver	0.333	0.348	0.092	0.089	0.117	<b>0.372</b>
FM Pan	0.223	0.227	0.138	0.132	0.186	<b>0.229</b>
FM Ver	0.339	0.366	0.137	0.136	0.151	<b>0.389</b>

**Table 6.4.1.7:** Shows the mean of the maximum, of the absolute maximum or absolute minimum cross correlations. The "Right-Plus-Left" have the highest CCF with the tracking.

Comparing [table 6.4.1.6](#) with [table 6.4.1.7](#) it can be seen that taking the maximum, of the absolute maximum or absolute minimum cross correlation function, the '**Right-Plus-Left**' indices gives the highest correlations for all trial types.

It seems somewhat surprising that the **RPL** index has higher CCF scores than the **RML** index for the panning trials; however for the panning trials they are not a lot higher. Whereas for the vertical trials, the **RPL** index has much higher scores than the **RML** index. Intriguingly the two asymmetry measures have the lowest scores of all.



Looking at the individual scores, the trials that have a **Negative Polarity** in one index are not the same trials to have a Negative Polarity in another index and in the **RPL** trials when the Min-CCF is larger than the Max-CCF it is a lot larger, but in Negative Polarity trials of **RML** there is not much difference between the Min-CCF and Max-CCF.

Alpha Power	Pan				Vertical			
	F3	F4	RML	RPL	F3	F4	RML	RPL
Both Up	0	0	+	0	+	+	0	+
Both Down	0	0	+	0	+	+	0	+
Left Up Right Down	-	+	+	0	0	0	0	+
Left Down Right Up	-	+	+	0	0	0	0	+
Just left Up	-	0	+	-	+	0	+	+
Just Right Up	0	+	+	+	0	+	-	+

**Table 6.4.1.8:** Shows the theoretical cross correlation functions of the tracking data with F3, F4, RML and RPL for the panning and vertical trials if the participants followed the instructions. Where '0' denotes no correlation, '+' signifies a positive correlation and '-' indicates a negative correlation.

In **table 6.4.1.8** the theoretical correlations of the tracking data with the 4 different indices are presented. For example in the panning trial, if the alpha power goes up on the left and down on the right the participants should move the slider to the left and this means the output values of the slider would go down (From 1000 to 1). Therefore as the values from the slider data goes down and the values of **F3** would go up there would be a negative correlation (-). But the values of **F4** would go down so there would be a positive correlation (+). For

the 'Right-Minus-Left', as alpha power goes up on the left and down on right, the **RMP** values would get smaller so there would be a positive correlation (+). For the 'Right-Plus-Left' **RPL** there would not be very much change so there would be a zero correlation (0).

This is why prior to the experiment it was believed the panning instructions would tend to have a higher cross correlation with the 'Right-Minus-Left' and the vertical instructions trials would have a higher cross correlation with 'Right-Plus-Left'.

However looking at the real means of the absolute maximum or minimum CCF scores in [table 6.4.1.6](#) clearly this theoretical correlation table is not supported by the empirical evidence. The findings hinge on the question of whether a CCF of around 0.2 is anything more than noise. Thus whether these findings have brought clarity to the decision is about which index to select is questionable.

However as the maximum of the absolute maximum or absolute minimum cross correlations with the tracking data with the "Right-Plus-Left" index in [table 6.4.1.7](#), is highest in all the tracking tasks, the **RPL** index will be selected for all subsequent statistical analysis of the tracking data. (The Spearman rank correlation coefficient ( $\rho$ ) was also computed at the lag from the maximum CCF for the RPL, but made very little difference so will not be reported).

### 6.4.2. Measures 2: EEG

This section is about the 8 EEG trials for the **AM** and **FM** Alpha EEG sonification neurofeedback from the 17 participants.

#### 6.4.2.1. EEG Session

Two channels of EEG were recorded using a Mitsar 202 EEG amplifier (Mitsar Co. Ltd., 1996) with a MCSCap elastic EEG-recording cap which has plastic holders for individual removable Ag/AgCl (Silver/Silver chloride) electrodes (Medical Computer Systems Ltd). The electrode locations were F3 and F4, the left and right frontal cortex with reference to Cz (on the top of the head) and the ground was at Pz, according to the International 10-20 electrode locations system (Jasper, 1958) (see [section 2.1.5](#)). The cap was placed on the head and NuPrep skin preparation gel was applied to the 4 electrode locations with a blunt wooden applicator stick to slightly abrade the skin in order to remove any excessive hair oil or dry skin to reduce the impedance to the skin. Then with a blunt 5ml syringe a small amount of electrode gel was squirted into the electrode cavity. It is the gel that touches the skin and conducts the electricity to the amplifier. (See appendix [A3.4](#) for datasheets). Headphones were put on and the impedances and quality of the EEG signal was checked using the commercial software WinEEG.

Then eight trials of 4 minutes each were recorded, first a pre-training baseline, next the five training trials, followed by a Transfer and a post-training baseline recording. All trials were recorded in an eyes closed condition and the raw EEG (i.e. all the frequencies the amplifier can measure) and the 8 to 12Hz Alpha

power were saved to the hard drive and then backed-up onto an encrypted drive.

By contrast with the tracking task, the same Instruction text was used for the AM and FM sonification with the words “**volume**” & “**frequency**” swapped.

### Training Instructions:

*“Next I will hook you up and record your EEG brainwaves and we will record a 4 minutes eyes closed baseline. Just sit still and relax try not to fall asleep or do any meditation.*

*Then you will hear the same sounds as in the tracking task, but this time they will reflect the activity in the front of your brain. So as your activity increases on the left-hand side the **volume (or frequency)** on the left will decrease and as your activity increases on the right-hand side the **volume** on the right will decrease.*

*Please close your eyes and try and increase the activity on the left of your brain and or decrease your brain activity on the right. You can do this by increasing the **volume** on the right hand side and or decreasing the **volume** on the left hand side.*

*Don't worry if you do not feel you have any control of the volume at the beginning.*

*You will have 5 trials of 4 minutes each, you will hear the sound of your brain activity in the sixth trial you must try and make the same brain activity but this time without any sound feedback. This is called a*

*'transfer trial' and is to see if you have any voluntary control over the activity without the feedback.*

*One of the problems with EEG is that it has a very low amplitude and can easily be contaminated by muscle and eye movement that also use electricity. So please try and sit as still and as comfortably as you can during the trials with your eyes closed and there will be a break to stretch and scratch between each trial. If you do need to stop and sneeze or something during the trial, just let me know and I can pause.*

*After the training we will record one more 4 minute eyes closed EEG and do the same two questionnaires as at the beginning"*

#### **6.4.2.2. EEG data processing chain**

##### **Data pre-processing:**

In "RStudio" the left (**F3**) and right (**F4**) Alpha values were extracted from the sonification software data files. For several reasons, the first 10 seconds of EEG data (i.e. 5001 data points) was discarded. Reasons include the following: some people can take a moment to settle after closing their eyes; alpha can take several seconds to kindle after closing the eyes at the start of each trial; and there is typically a variation in the lag from the pressing of the record button to the EEG amplifier sending the data, The next 200 seconds of data was recorded. Consequently, all EEG files were 100,000 data points long – where needed, some EEG data was cut from the end of the files.

### EEG Artifacts:

The study was designed to minimise non EEG related artifacts during the recording sessions, by recording in an eyes closed condition, with short trials and regular breaks to allow the participants to stretch, scratch and blink, as well as allowing the participants to see their own real-time EEG at the beginning to demonstrate the sources of artifact and giving coaching on how to reduce them. Visual inspection of all the files confirmed very clean EEG with few artifacts.

Thus in R-Studio, in order to exclude only extreme data points that were likely to come from non EEG related artifacts such as eye blink, the EEG data was z-transformed and any data values greater than the **3 Z-Score** (i.e. 99.7%) for each file were capped at the 3 Z-Score value. The Z-Score threshold, ranged from 4.01 to 20.89  $\mu\text{V}$  with a mean of 10.67. Furthermore, in order to reduce the effect of residual artifacts that were not excluded by the Z-Score cap, such as eye blinks, which can have short duration but large amplitude activity, the **median** Alpha EEG value was taken for the F3 and F4 channels for the statistical analysis.

### EEG Measures:

Similarly to the tracking trials, there were a number of measures that could be derived from the **F3** and **F4** EEG channels that were sonified.

### Asymmetry:

Just as with the EEG in the tracking trials, there are two main ways commonly used in the literature of computing Frontal Alpha Asymmetry from left (F3) and

right (F4) Alpha. The first, **Index 1** is **FAA** =  $(F4 - F3)/(F4 + F3)$ , (Allen, Harmon-Jones and James H. Cavender, 2001) which can range from 1 to -1 and the second, **Index 2**, is computed by subtracting the natural log of F3 from the natural log F4 **Log-FAA** =  $\log(F4) - \log(F3)$ , (Stewart et al., 2014; Allen, Harmon-Jones and James H. Cavender, 2001) which can typically range from plus to minus 15.

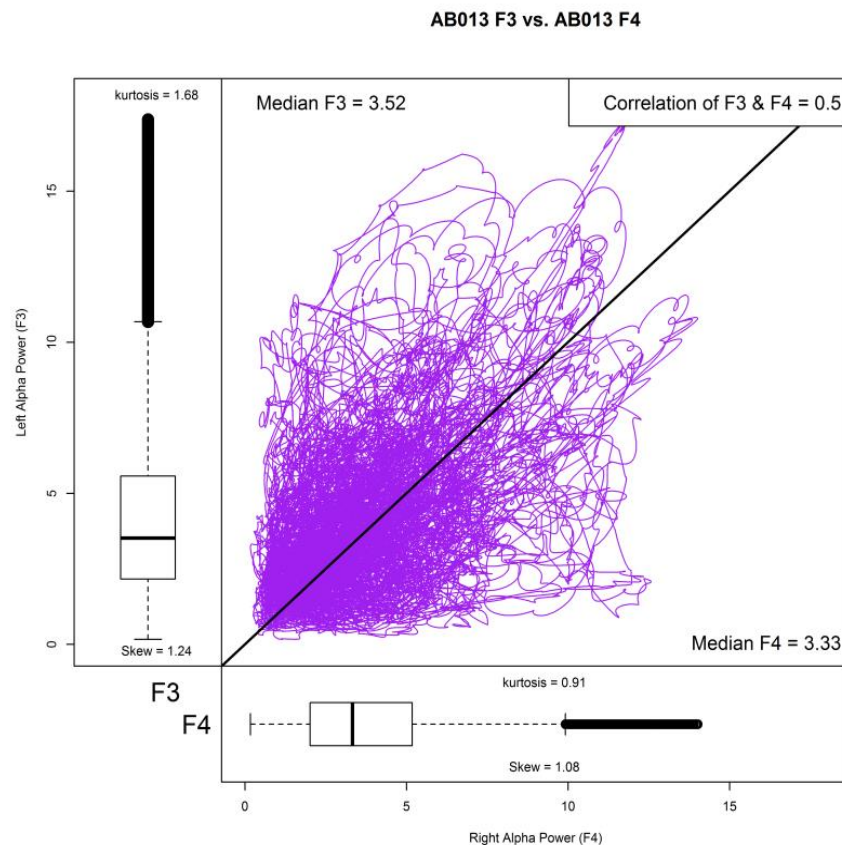
What is surprising about both these asymmetry measures is that they do not take into account the overall amplitude of both channels. So for example, Left = 30  $\mu V^2$  & Right = 30  $\mu V^2$  is likely to be a very different brain state then Left = 3  $\mu V^2$  & Right = 3  $\mu V^2$ , but both of these Indices would equal zero Frontal Alpha Asymmetry.

This analysis will use the time series version for the statistical analysis:

**FAA** = median of  $((F4 \text{ Alpha} - F3 \text{ Alpha}) / (F4 \text{ Alpha} + F3 \text{ Alpha}))$  (**Eq. 6.4.2.2.1**)

**Log-FAA** = median of  $(\log(F4 \text{ Alpha}) - \log(F3 \text{ Alpha}))$  (**Eq. 6.4.2.2.2**)

In **figure 6.4.2.2** the Alpha from F4 is plotted against F3 for each data point for the 200 second trial of a single person. The 'Box and Whisker' plot of the left and bottom show how skewed the Alpha EEG is and in this example, there is a 0.5 correlation between F4 and F3. It seems that the majority of the lines are moving along the 45 degree axis (i.e. both F3 and F4 going up and down together) but there are some prominent tangential excursions. i.e. as right goes up left goes down and vice versa.



**Figure 6.4.2.2:** shows F4 vs. F3 for each data point for a 200 seconds trial. The Box and whisker plot on the left is of the F3 Alpha EEG and on the bottom is of F4.

Thus for compatibility with the tracking analysis and because it had the highest CCF with the tracking data, the “Right-Plus-Left” **RPL** index will be used but because the RML has such a low CCF in the tracking data it will be dropped from subsequent analysis.

Thus the five indices that will be used in the EEG analysis are Left Alpha EEG (**F3**), right Alpha EEG (**F4**), the ‘Frontal Alpha Asymmetry’ between F3 and F4 (**FAA**), the Log ‘Frontal Alpha Asymmetry’, (**Log-FAA**) and the ‘Right-Plus-Left (**RPL**).



## 6.5. Results

The following section will present the results for experiment 3 for the; **Measures 1:** tracking data, **Measures 2:** the EEG data, **Measures 3:** the NASA-TLX and the **Measures 4:** emotional rating scores.

### 6.5.1. Measures 1: Tracking

As explained in [section 6.4.1.5](#), the tracking accuracy scores are computed by the 'Cross Correlation Functions' of the tracking data with the "Right-Plus-Left" Alpha EEG measure and taking the 'Absolute Maximum' of the maximum or minimum CCF. Because each person does two tracking tasks (Pan and Vertical) in two different sonification sessions (AM and FM), there are four tracking trials **AM-Pan** and **FM-Pan** as well as **AM-Vertical** and **FM-Vertical**.

The following tracking accuracy scores will be analysed to establish; **6.5.1.1:** If there is a difference in the tracking accuracy scores due to the order that the 'Pan' and 'Vertical' tracking trials were conducted. **6.5.1.2:** If gender had an effect on tracking scores. **6.5.1.3:** If there was a difference between the 'Pan' and 'Vertical' tracking trials. **6.5.1.4:** If there is a difference between AM and FM sonifications tracking trials.

#### 6.5.1.1. Tracking: By Order

Four independent-sample t-tests were conducted to test if the order that the tracking trials were carried out made a difference to the tracking accuracy scores. The two groups were people who did the Pan trials first versus people

who did the vertical trials first. The Levene's test for 'Equality of Variances' for all four measures was not significant so 'equal variances' was assumed. Estimate effect size for the T-Tests were given by Cohen's (d) (Cohen, 1969).

Trial Name	Pan First		Ver First		T-Test
	Mean	StD	Mean	StD	
<b>AM-Pan (N.8)</b>	0.203	0.084	0.283	0.067	t(15)= -2.171, p = <b>0.046</b> , d = 1.05
<b>AM-Vertical (N.9)</b>	0.352	0.111	0.391	0.111	t(15)= -0.702, p = <b>0.049</b> , d = -0.41
<b>FM-Pan (N.7)</b>	0.230	0.131	0.229	0.148	t(15)= 0.024, p = <b>0.982</b> , d = -0.01
<b>FM-Vertical (N.10)</b>	0.433	0.079	0.358	0.091	t(15)= 1.768, p = <b>0.097</b> , d = -0.88

**Table 6.5.1.1:** Tracking by Order: Shows the Mean, Standard Deviation and T-Test of the Cross Correlations scores of the four tracking tasks split by order.

**Table 6.5.1.1** shows that for the AM tracking trials there is a slight significant difference between the trials where people started with the Panning trial (N.8) compared to those that started with the Vertical trial (N.9).

For the FM tracking trials the p-values are not significant, panning trial first (N.7) and vertical trial first (N.10). Therefore, the null hypothesis is **NOT** rejected for FM as there is no evidence of a difference in the Absolute Maximum CCF (**Max-RPL**) due to the order in which the participants did the tracking trials.

#### 6.5.1.2. Tracking: By Gender

Because there can be a gender difference in hearing acuity across the frequency spectrum (Murphy and Gates, 1997), four, two-tailed, independent-sample t-tests were conducted to see if gender had an effect on tracking scores, shown in **table 6.5.1.2**. The Levene's test for 'Equality of Variances' for all

four measures was not significant, so 'Equal variances' was again assumed and estimate effect size for the T-Tests was again given by Cohen's (d).

Trial Name	Female (N.8)		Male (N.9)		T-Test
	Mean	StD	Mean	StD	
<b>AM-Pan</b>	0.240	0.099	0.251	0.073	t(15)= - 0.248, p = <b>0.808</b> , d = 0.126
<b>AM-Vertical</b>	0.361	0.115	0.383	0.110	t(15)= - 0.400, p = <b>0.695</b> , d = 0.196
<b>FM-Pan</b>	0.215	0.136	0.242	0.145	t(15)= - 0.401, p = <b>0.694</b> , d = 0.192
<b>FM-Vertical</b>	0.385	0.085	0.393	0.095	t(15)= - 0.181, p = <b>0.858</b> , d = 0.089

**Table 6.5.1.2:** Tracking by Gender: Shows the Mean, Standard Deviation and T-Test of the Cross Correlations scores of the four tracking tasks split by Gender.

In **Table 6.5.1.2**, all P-values are greater than 0.05, thus it can be concluded than there is no evidence that gender had an effect on tracking scores.

### 6.5.1.3. Tracking: By Pan and Vertical tracking trials.

Two, paired-sample two-tailed T-Tests, were run on the **AM-Pan** versus the **AM-Vertical** and the **FM-Pan** versus **FM-Vertical**.

Trial	Pan		Vertical		T-Test
	Mean	StError	Mean	StError	
<b>AM</b>	0.246	0.020	0.372	0.027	t(16)= -4.855, p = <b>0.000</b> , d = 1.177
<b>FM</b>	0.229	0.033	0.389	0.022	t(16)= -4.662, p = <b>0.000</b> , d = 1.131

**Table 6.5.1.3:** Tracking: Pan vs. Vertical by sonification AM and FM.

There is a large statistical difference between the panning and vertical tracking trials for both sonification techniques and looking at the means of the tracking accuracy in [table 6.5.1.3](#), the 'Vertical' trials have a higher score than the 'Panning' tracking trials for both the AM and FM sonifications.

#### 6.5.1.4. Tracking: By AM and FM Sonification

Two, paired-sample two-tailed T-Tests were run between **AM** versus **FM**. for both the pan and vertical tracking trials.

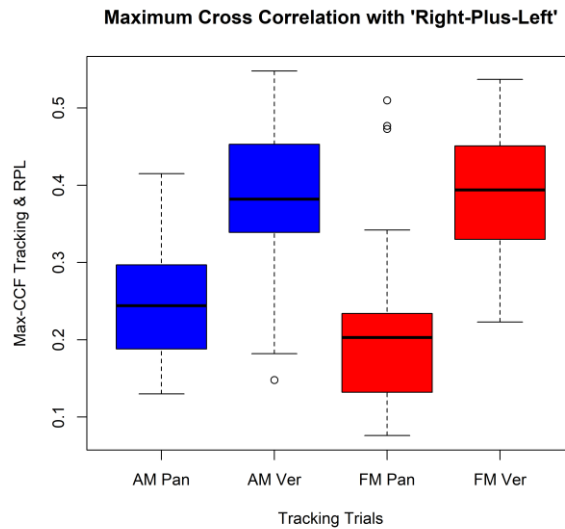
Trial	AM		FM		T-Test
	Mean	StError	Mean	StError	
<b>Pan</b>	0.246	0.020	0.229	0.033	t(16)= 0.590, p = <b>0.590</b> , d = 0.143
<b>Vertical</b>	0.372	0.027	0.389	0.022	t(16)= -0.715, p = <b>0.485</b> , d = -0.173

**Table 6.5.1.4: Tracking:** AM vs. FM sonification for both pan and vertical tracking trials.

As seen in [table 6.5.1.4](#), there is no difference between the AM vs. FM sonification techniques on either of the pan and vertical tracking tasks.

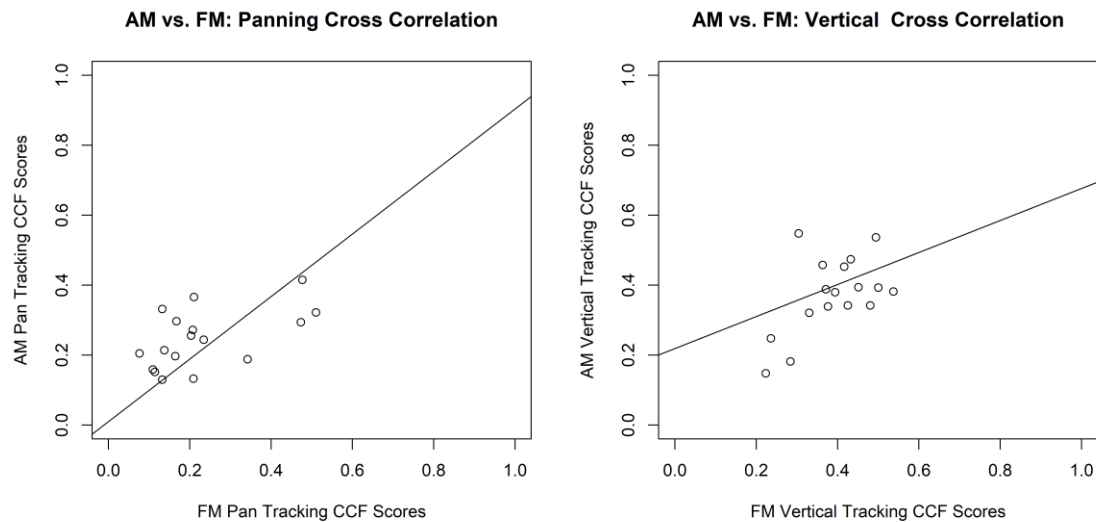
#### 6.5.1.5. Tracking: By Sonification type and Tracking instruction

This next section will present the analysis of the two different tracking trial types (Pan vs. Vertical) for the two different sonification techniques (AM vs. FM).



**Figure 6.5.1.5.1:** Shows a Box-&-Whisker plot of the median and quartiles of the 'Absolute Maximum Cross Correlation' scores between the Tracking and the 'Right-Plus-Left' index for the 4 tracking trials. AM in blue and FM in red and "Ver" is the vertical trials.

**Figure 6.5.1.5.1** shows that the vertical trials achieved higher tracking accuracy scores for both sonifications than the panning trials. Because there seems to be a pattern in the tracking scores with the two vertical trials for both AM and FM sonification having similar scores and the two panning trials having similar scores, as seen in **Figure 6.5.1.5.2**, two scatter plots were created in order to compare the two vertical trials to each other and the two panning trials.



**Figure 6.5.1.5.2:** Scatter plot of AM (y-axis) vs. FM (x-axis) of the tracking accuracy scores. Left plot is of the Panning Tracking trials and the right plot is of Vertical Tracking trials.

**Figure 6.5.1.5.2**, shows the panning tracking trials have a correlation of 0.548 between the AM-Pan versus the FM-Pan and the vertical tracking trials have a correlation of 0.544 between AM-Vertical versus FM-Vertical.

Thus it can be concluded there was not a statistical difference between the two sonification tracking trials. But there is a statistical difference between the **Pan** and **Vertical** tracking trials, although of course this was not the point of the experiment.

### ANOVA of Sonification and Tracking

In order to control for repeated statistical comparisons of the T-Tests, a two by two repeated measures ANOVA (Sonification: AM vs. FM) x (Tracking: Pan vs. Vertical) was run in SPSS v2.1.

**Sonification:** AM vs. FM  $F(1,16) = 0.000$ ,  $p = 0.992$ ,  $\eta^2 = 0.00$ . With **AM** ( $M = 0.309$ ,  $SE = 0.020$ ) and **FM** ( $M = 0.309$ ,  $SE = 0.023$ )

**Tracking:** Pan vs. Vertical  $F(1,16) = 29.204$ ,  $p = 0.000$ ,  $\eta^2 = 0.646$ . With **Pan** ( $M = 0.237$ ,  $SE = 0.024$ ) and **Vertical** ( $M = 0.381$ ,  $SE = 0.021$ ).

This ANOVA analysis confirms the T-Tests findings above, that there was not a statistical difference between the two sonification tracking trials. But there is a statistical difference between the Pan and Vertical tracking trials.

Thus in summary, the results of the **tracking** task showed that there was no difference between the AM or FM sonifications for either of the tracking trials, but the 'Vertical' tracking task had a significantly higher tracking accuracy score than the 'Panning' task for both the AM and FM sonifications. This highlights the importance of the instructions for the tracking task. Also it should be noted that the mean of the 'Absolute Maximum Cross Correlation' scores was 0.309 with a minimum of 0.076 and maximum of 0.548 which is not very high and has some extremely low scores.

### 6.5.2. Measures 2: EEG

This section will present the analysis of **AM** and **FM** sonification neurofeedback training data from the two channels of Alpha EEG and the derived indices, for the 8 trials from the 17 participants.

The five indices are Left Alpha EEG (**F3**), right Alpha EEG (**F4**), the 'Frontal Alpha Asymmetry' between F3 and F4 (**FAA**), the Log 'Frontal Alpha Asymmetry', (**Log-FAA**) and the 'Right-Plus-Left (**RPL**).

### 6.5.2.1. Normality Test

In R-Studio, Line plots, Histogram and Q-Q were plotted for all the EEG files and descriptive statistics computed. It was found that the majority of the **F3** and **F4** Alpha EEG files were positively skewed and leptokurtic. The range of **Skew** was **0.37** to **7.65** with the Standard error of skewness of 0.007<sup>6</sup> and thus a Threshold of 0.015<sup>7</sup>. The **Kurtosis** had a range of **-0.33** to **87.82** with standard error of kurtosis of 0.015<sup>8</sup> and thus a Threshold of 0.030<sup>9</sup> thus only 25 of the 544 files (4.6%) were within thresholds for normal skew and kurtosis. See [figure 6.5.2.1.1](#) for line, histogram and Q-Q plot of raw and artifacted data for comparisons.

For the 'raw' un-artifacted Alpha EEG of 200 seconds, the **Anderson-Darling** test of normality had a range from **171** to **8232** with all p-values smaller then **0.0001**, and the **Kolmogorov-Smirnov** comparison to a normal distribution ranged from **0.023** to **0.18** with all p-values smaller then **0.0001**. Thus both the Anderson-Darling and Kolmogorov-Smirnov test indicated the EEG data did **NOT** have a normal distribution. The Hartigans' dip test for unimodality, found **111** out of **544** (8 trials \* two sonification \* two EEG channels \* 17 participants = 544) EEG records had a "D" score greater than **0.0017** and a **p < 0.05**, showing that 20% of the F3 and F4 Alpha EEG files were NOT unimodal.

After **artifacting** (e.g. removing blinks and muscle movement from the EEG trace), the p- values for the Anderson-Darling were all still **p < 0.05**. But after the **Hartigans' dip test**, there was only **9** files out of 544 had a **p < 0.05**, showing that

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<sup>6</sup> (i.e.  $\sqrt{6/1000000}$ )

<sup>7</sup> (i.e.  $1.96 * 0.0077$ )

<sup>8</sup> (i.e.  $\sqrt{24/1000000}$ )

<sup>9</sup> (i.e.  $1.96 * 0.015$ )



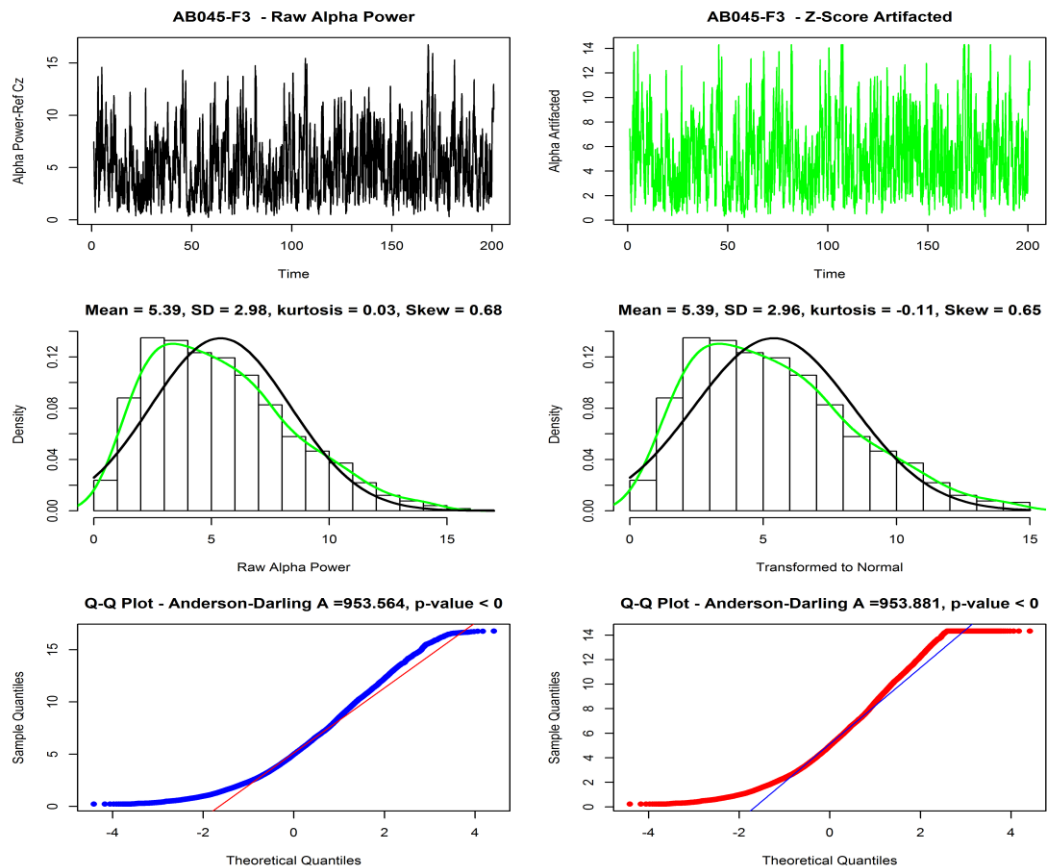
only 1.65% of the EEG files were NOT unimodal. This suggests the non unimodality of the raw EEG data was probably due to extreme values of artifacts.

For the **FAA**, despite the Histogram and QQ plots, all looking as if the files had a normal distribution, the Anderson-Darling test, had a range from 3.05 to 199.18 with all  $p < 0.000$  and Kolmogorov–Smirnov had a range of 0.006 to 0.036 with only one file having a  $p > 0.05$ . Hartigans' dip test, found **15** files had a  $p < 0.05$  and score with a minimum of  $7.12 \times 10^{-4}$  and a maximum of 0.0048.

The **Log-FAA** had an Anderson-Darling test ranging from 8.70 to 525 with all trials below  $p < .05$  and Kolmogorov–Smirnov all around zero and all P-values below 0.05, also, 87 trials showing NON unimodality.

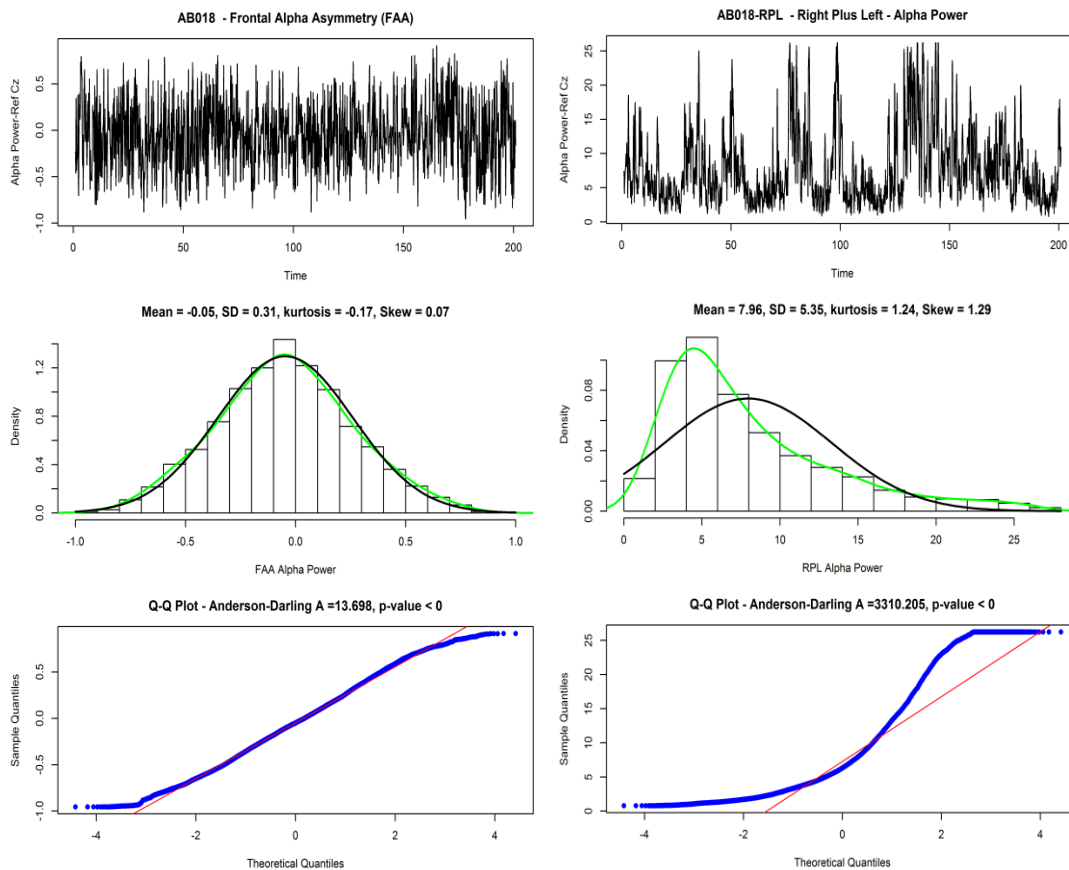
For the **Right Plus Left** measure, the Anderson-Darling test of normality had a range from **51.65** to **5495.9** with all p-values smaller than **0.00**, and the Kolmogorov–Smirnov comparison to a normal distribution ranged from **0.025** to **0.179** with all p-values smaller than **0.001**. Thus both the Anderson-Darling and Kolmogorov–Smirnov test indicated the **RPL** Alpha EEG data did NOT have a normal distribution. The Hartigans' dip test had a range from **0.00** to **0.0115** and found **87** files out of 272 had a  $p < 0.05$  that is **42%** of the RPL alpha EEG files were NOT unimodal. It would appear that the P-values are all so small because the EEG files have 100,000 data points each.

(For additional information, see appendix **A5.3 Supplementary Data** - Experiment 3, Anderson-Darling, Kolmogorov–Smirnov and Hartigans' dip test Max, Min and P-values for the Raw Alpha, Artifacted Alpha, FAA, Log-FAA, RPL).



**Figure 6.5.2.1.1:** The top row shows line plots of time series data. In the middle row, the histogram with the green line shows the probability distribution of the data, while the black line shows the probability distribution of the normal curve with the same mean and standard deviation. The bottom row shows, Q-Q plots of the data against the normal distributions. The left-hand column shows 200 seconds of 'raw' un-artifacted Alpha EEG data and the right-hand column shows the same data after artifacting for comparison. Note the flat section of the red line on the top right hand of the QQ Plot, this is the artifacted data where the values were capped to the 3 Z-Score.

**Figure 6.5.2.1.1**, shows that the raw alpha EEG is positively skewed, and that artifacting did not change the normality of the data much - but it did reduce the number of EEG records that were not unimodal from 111 to 9.



**Figure 6.5.2.1.2:** Line plot, Histogram and, Q-Q plot with the same data as in **figure 6.5.2.1.1**. Plots on the left are of the frontal Alpha asymmetry FAA. On the Right is the Right-Plus-Left RPL.

In **figure 6.5.2.1.2** the Frontal Alpha Asymmetry (FAA) (i.e. Index 1, see [section 6.4.1.2](#)) gives a very normal looking distribution but the RPL transformation exacerbates the deviations in normality seen in F3 above. Looking at the line plots on the top left of **figure 6.5.2.1.2**, the **FAA** seems to obscure the typical

morphology of the EEG and it looks more like noise and is very different from the line plots of RPL on the top right and the raw alpha of **F3** in [figure 6.5.2.1.1](#).

This distortion to the morphology by the asymmetry transformation is one of the reasons why this research chose to sonify the two individual Alpha EEG channels of F3 and F4 separately rather than calculate the Alpha asymmetry first and then sonify the single stream of FAA as it was felt this may lose some of the temporal complexity of the raw Alpha EEG.

#### **6.5.2.2. Data Transformations to Normality**

A number of different data transformations commonly used in EEG analysis were tested in order to improve the normality: i.e.  $-1/x$ ,  $-1/\sqrt{x}$ ,  $\log(x)$ ,  $\sqrt{x}$ ,  $x^2$ . A potentially useful transformation was reported by van Albada and Robinson (van Albada and Robinson, 2007) and these researchers kindly provided the Matlab code.

Most relevantly van Albada suggested that although the “Log” transformation is perhaps the most common normalisation procedure used in the EEG field, it has a tendency to overcorrect the Alpha EEG band and this was found to be the case in this present experiment. The van Albada transformation avoids this problem. Therefore all the EEG files were transformed in Matlab using the van Albada transformation.

After the Van Albada transformation the Hartigans' dip test for unimodality was found to have a  $D = 0.00$  and a  $p\text{-value} = 1$  for all files.

Descriptive statistics were computed on the 1: “Raw” un-transformed, un-artifacted data, 2: the Z-scored artifacted data and 3: the EEG that had been

both Z-scored artifacted and transformed. It was found that although the artifacted and normally transformed data does give nicely normal distributions, it does create negative values. The natural logarithm of a negative number is undefined and causes problems for the asymmetry calculation. Furthermore as both the T-Test and the ANOVA are reasonably robust to deviations from normality, it was decided that the artifacted but un-transformed Alpha EEG data would be used for analysis.

### 6.5.2.3. Descriptive Statistics

First descriptive statistics were computed on the median of the artifacted **F3** and **F4** plus the Asymmetry measures **FAA** and **Log-FAA** as well as the 'Right-Plus-Left' (**RPL**)'

**Table 6.5.2.3**, shows that **F3** and **F4** have a very similar data range, the two asymmetry measures both have negative numbers and the **Log-FAA** has double the range of **FAA** but a similar median and RPL have all positive numbers.

	F3 Median	F4 Median	FAA	Log-FAA	RPL
<b>Max.</b>	8.098	8.347	0.097	0.195	14.995
<b>3rd Qu</b>	4.566	4.655	0.018	0.036	8.944
<b>Mean</b>	3.873	3.910	-0.004	-0.009	8.004
<b>Median</b>	3.882	3.983	-0.003	-0.006	8.029
<b>1st Qu</b>	3.074	3.126	-0.028	-0.056	7.415
<b>Min.</b>	1.530	1.560	-0.119	-0.238	3.150

**Table 6.5.2.3:** shows the quartiles of F3, F4, FAA, Log-FAA and RPL after artifacting. There is around a plus and minus 10% variation in the FAA and a 20% for the Log-FAA.

#### 6.5.2.4. Statistical Analysis

The 'Right-Minus-Left' index (**RML**) was dropped from the EEG analysis as there was no particular rationale for its use in the training and it was found not to be useful in the tracking analysis.

Exploratory analysis was conducted on all 8 trials of the AM and FM (N. 16) training of all five remaining measures of **F3**, **F4**, **FAA**, **Log-FAA**, **RPL** (N.80) and it was concluded that the asymmetry measures **FAA** and **Log-FAA** did not provide any additional useful information greater than F3 and F4. (See appendix [A5.3](#) SPSS Statistics Output document "EX3-EEG-All-Ttests" for all T-tests and ANOVA).

Furthermore the Test-retest reliability coefficient, i.e. the correlation between the baseline trial of the first and second session was very low for the **RML** = 0.380, **FAA** = 0.251 and **LogFAA** = 0.251 indices but very high for **F3** = 0.880, **F4** = 0.885 and **RPL**= 887 indices.

Therefore three indices **F3**, **F4** and **RPL** were carried forward for further analysis as follows:

**Order:** **AM** Trials First vs. **FM** Trials First (see [section 6.5.2.5](#))

**Gender:** **Female** vs. **Male** (see [section 6.5.2.6](#))

**Training vs. Sonification** for four pairs of trials: (see [section 6.5.2.7](#))

**Trial Pair 1:** Trial 1 vs. Trial 8 - **Pre** vs. **Post**

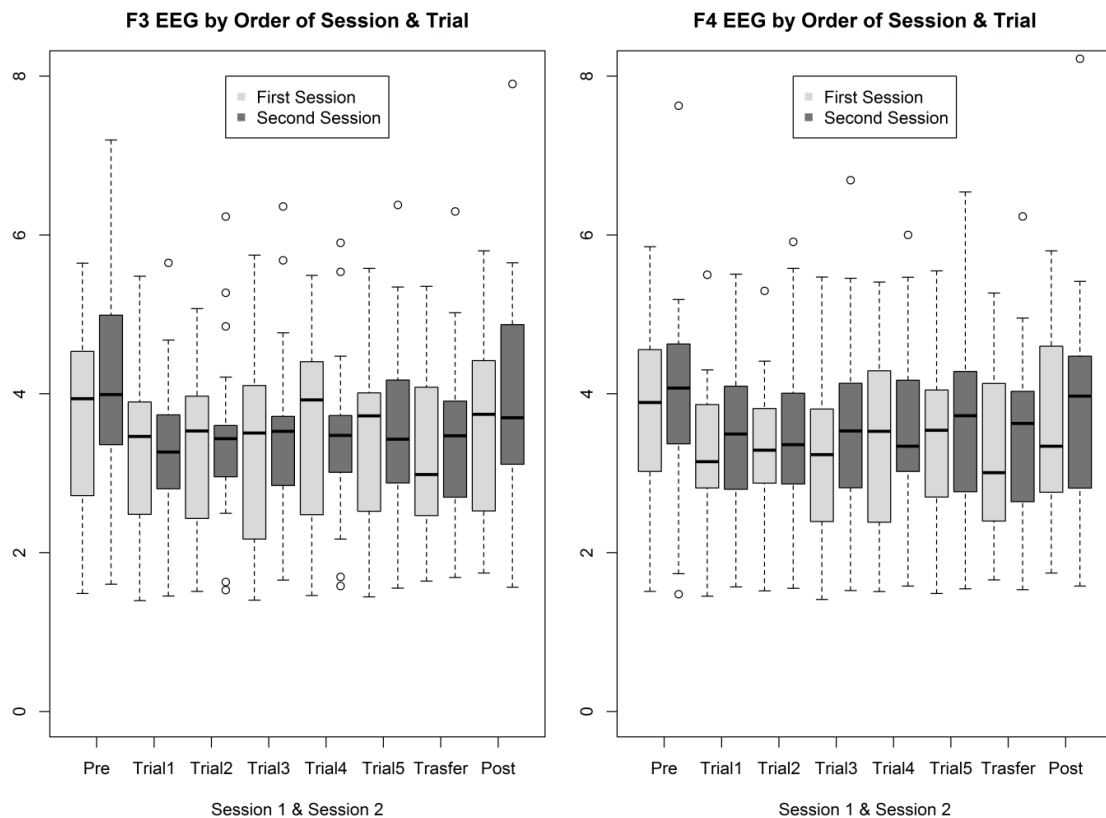
**Trial Pair 2:** Trial 1 vs. Trial 7 - **Pre** vs. **Transfer**

**Trial Pair 3:** Trial 7 vs. Trial 8 - **Transfer** vs. **Post**

**Trial Pair 4:** Trial 2 vs. Trial 6 - **First** vs. **Last Training**

### 6.5.2.5. Training: By Order

An independent-sample t-test of **F3**, **F4** and **RPL** by **order** for all trials did not show any statistical difference between the participants that did the AM sonification for the first training session versus those that did FM first. See [figure 6.5.2.5](#).



**Figure 6.5.2.5:** Box-&-Whisker plot shows the median and quartiles of F3 (left) and F4 (right) for all 8 training trials sorted by presentation order and grouped across sonifications. So each box is an average of both the AM and FM trials for each training trial time points. Light gray is the first trial people did and the dark gray is the second trial regardless of sonification. (The open circles are outliers, i.e. 1.5 times smaller or larger than the interquartile range from the first or third quartile).

To check if people differed between their Alpha levels at the start of the two baseline sessions due to the time of day effect, a paired-sample t-test of **F3** and **F4** for **trial 1**, was run and found no difference with **F3**: First session vs. Second session giving a  $t(16) = -1.330$ ,  $p = 0.202$ ,  $d = -0.168$  and **F4**: First session vs. Second session giving,  $t(16) = -1.751$ ,  $p = 0.099$ ,  $d = -0.206$ . Thus there was no difference in the baseline Alpha EEG levels between the two sessions.

#### 6.5.2.6. Training: By Gender

A second independent-sample t-test of **genders**, Female N. = 8 and Male N. = 9, did not show any difference between any of the trials for any of the measures, with the lowest p-value of,  $t(15) = 1.529$ ,  $p = 0.147$ . (See [appendix A5.3](#))

#### 6.5.2.7. Training vs. Sonification

This next section will analyse AM vs. FM sonifications, with three different EEG parameters, between four different pairs of training trials.

The three EEG parameters are the Alpha from the left (**F3**), from the right (**F4**) and the derived measure of Right-Plus-Left (**RPL**).

The four training trials are; **Trial Pair 1**: will compare the **Pre** vs. **Post** trials; **Trial Pair 2**: will look at the **Pre** vs. **Transfer** trials; **Trial Pair 3**: will analyse the **Transfer** vs. **Post** trials; and lastly the **Trial Pair 4**: will compare the **First** vs. **Last Training** trials.

The three statistical comparisons are the comparison between AM vs. FM **Sonifications** for the **Trial pair** and the Interaction between **Sonifications** and **Trials**.



### **Trial Pair 1: Trial 1 vs. Trial 8 - Pre vs. Post**

A two-way repeated measures ANOVA was run in SPSS for the 3 measures **F3**, **F4** and **RPL**. This is a 2 by 2: i.e. 2 sonifications, **AM** and **FM** by 2 trials or time points

**Pre vs. Post:**

#### **For Left Alpha - F3:**

**Sonification:** AM vs. FM,  $F(1,16) = 1.840$ ,  $p = 0.194$ ,  $\eta^2 = 0.103$ , with **AM** ( $M = 3.955$ ,  $SE = 0.347$ ) and **FM** ( $M = 3.712$ ,  $SE = 0.310$ )

**Trials:** Pre vs. Post,  $F(1,16) = .333$ ,  $p = 0.572$ ,  $\eta^2 = 0.020$ , with **Pre** ( $M = 3.867$ ,  $SE = 0.322$ ) and **Post** ( $M = 3.800$ ,  $SE = 0.322$ ).

Therefore there is no evidence of a difference in Alpha EEG levels for F3 between sonifications, or of a difference between the Pre vs. Post trials.

Interaction between **Sonifications** and **Trials** was,  $F(1,16) = 1.540$ ,  $p = 0.232$ ,  $\eta^2 = 0.088$ , with means of **Pre-AM** ( $M = 4.027$ ,  $SE = 0.344$ ), **Pre-FM** ( $M = 3.884$ ,  $SE = 0.364$ ), **Post-AM** ( $M = 3.707$ ,  $SE = 0.320$ ) and **Post-FM** ( $M = 3.716$ ,  $SE = 0.311$ ), did not show a significant effect either.

#### **For Right Alpha - F4:**

**Sonification:** AM vs. FM,  $F(1,16) = 0.510$ ,  $p = 0.485$ ,  $\eta^2 = 0.031$ , with **AM** ( $M = 3.874$ ,  $SE = 0.367$ ) and **FM** ( $M = 3.736$ ,  $SE = 0.296$ )

**Trials:** Pre vs. Post  $F(1,16) = .117$ ,  $p = 0.737$ ,  $\eta^2 = 0.007$ , with **Pre** ( $M = 3.823$ ,  $SE = 0.325$ ) and **Post** ( $M = 3.786$ ,  $SE = 0.322$ ).

Interaction between **Sonifications** and **Trials** was,  $F(1,16)= 1.410$ ,  $p = 0.252$ ,  $\eta^2 = 0.081$ . With means of **Pre-AM** (M= **3.933**, SE= 0.362), **Pre-FM** (M= **3.814**, SE= 0.384), **Post-AM** (M= **3.714**, SE= 0.308) and **Post-FM** (M= **3.758**, SE= 0.295), did not show a significant effect either.

Thus again there is no evidence of a difference in Alpha EEG levels for F4, between sonifications or the Pre vs. Post trials or the Interaction.

#### For Right-Plus-Left - RPL:

**Sonification:** AM vs. FM  $F(1,16)=1.029$ ,  $p = 0.325$ ,  $\eta^2 = 0.060$ , with **AM** (M= **7.892**, SE= .715) and **FM** (M= **7.518**, SE= 0.614).

**Trials:** Pre vs. Post,  $F(1,16)= 0.173$ ,  $p = 0.683$ ,  $\eta^2 = 0.011$ , with **Pre** (M= **7.750**, SE= 0.651) and **Post** (M= **7.660**, SE= 0.648).

Interaction between **Sonifications** and **Trials** was,  $F(1,16)= 1.188$ ,  $p = 0.292$ ,  $\eta^2 = 0.081$ , with means of **Pre-AM** (M=**8.004**, SE= 0.707), **Pre-FM** (M= **7.780**, SE= 0.747), **Post-AM** (M= **7.497**, SE= 0.636) and **Post-FM** (M= **7.540**, SE= 0.614), did not show a significant effect either.

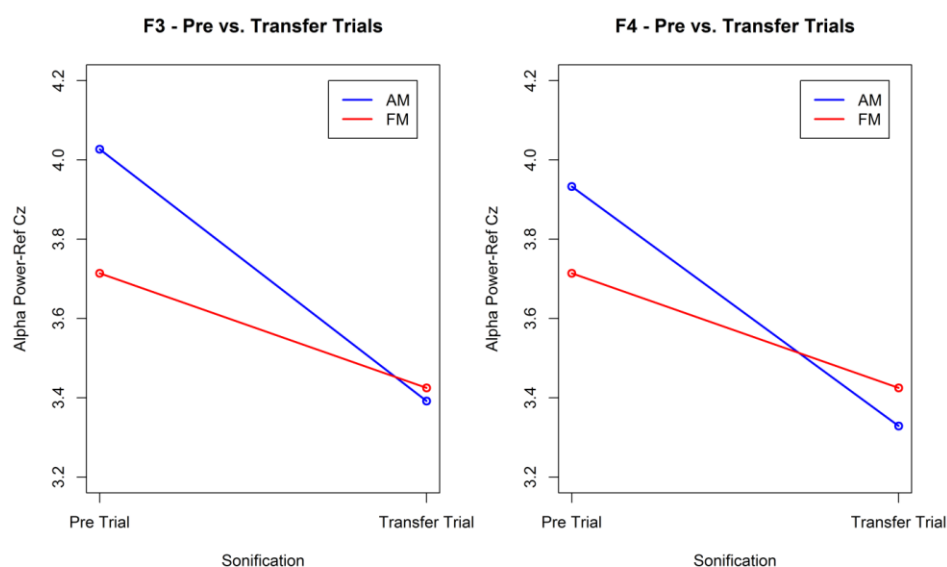
Thus again there is no evidence of a difference in Alpha EEG levels, between sonification methods or the Pre vs. Post trials or the Interaction for the RPL measure, or F3 or F4.

This comparison between Pre vs. Post trials would have been the best evidence for the utility of EEG Sonification, but it was the least likely change, as it would imply a shift in brain activity in one session, even when the participants were not attempting to change their brain state.

### Trial Pair 2: Trial 1 vs. Trial 7 - **Pre** vs. **Transfer**

A second two-way repeated measures ANOVA was run on the same measures but this time between the **Pre** vs. **Transfer** trials. In the Transfer trial participants were instructed to keep trying to produce the brain activity that they had been trying to make in the feedback trials but this time, without any sound feedback. If they were able to make a change between these two trials, despite not showing a Pre to Post change, this would have been evidence of volitional control of their own Alpha brain waves, with the assumption that they could not have done this before the session, as the instruction to “increase Alpha on the right and or decrease it on the left”, would have been meaningless before the training.

A two-way repeated measures ANOVA in SPSS for the 3 measures of **F3**, **F4** and **RPL** was computed. This is a 2 by 2: i.e. 2 sonifications, **AM** and **FM** by 2 trials or time points **Pre** vs. **Transfer**.



**Figure 6.5.2.7.1:** Left: Alpha levels for F3 in the pre baseline and the Transfer trials for the AM (blue) and FM (red). Right is the same for F4.

#### For Left Alpha - F3 - Pre vs. Transfer:

**Sonification:** AM vs. FM,  $F(1,16)= 1.321$ ,  $p = 0.267$ ,  $\eta^2 = 0.076$ , with AM ( $M= 3.709$ ,  $SE= 0.303$ ) and FM ( $M= 3.537$ ,  $SE= 0.277$ )

**Trials:** Pre vs. Transfer,  $F(1,16)= 7.585$ ,  $p = 0.014$ ,  $\eta^2 = 0.322$ , with **Pre** ( $M= 3.867$ ,  $SE= 0.322$ ) and **Transfer** ( $M= 3.379$ ,  $SE= 0.263$ ).

Interaction between **Sonifications** and **Trials** did show a significant effect with,  $F(1,16)= 8.640$ ,  $p = 0.010$ ,  $\eta^2 = 0.351$ , with: **Pre-AM** ( $M= 3.933$ ,  $SE= 0.362$ ), **Pre-FM** ( $M= 3.329$ ,  $SE= 0.298$ ), **Transfer-AM** ( $M= 3.714$ ,  $SE= 0.308$ ) and **Transfer-FM** ( $M= 3.425$ ,  $SE= 0.258$ ). See [Figure 6.5.2.7.1](#).

There is no evidence of a difference in Alpha EEG levels, between sonifications but there is a difference between Pre vs. Transfer trials for both sonifications together and also an 'Interaction Effect' between the four trials. Unfortunately however, F4 showed the same pattern of an Alpha decrease from Pre to Transfer, as F3 for both sonifications, whereas the training instructions were to increase the alpha at F4 and decrease it at F3, thus the training protocol was not successful in modifying the alpha levels in the chosen direction.

#### For Right Alpha - F4- Pre vs. Transfer:

**Sonification:** AM vs. FM,  $F(1,16)= 0.160$ ,  $p = 0.695$ ,  $\eta^2 = 0.010$ . With **AM** ( $M= 3.631$ ,  $SE= 0.320$ ) and **FM** ( $M= 3.570$ ,  $SE= 0.267$ ).

**Trials:** Pre vs. Post,  $F(1,16)= 12.272$ ,  $p = 0.003$ ,  $\eta^2 = 0.434$ . With **Pre** ( $M= 3.823$ ,  $SE= 0.325$ ) and **Transfer** ( $M= 3.377$ ,  $SE= 0.268$ ).

Interaction between **Sonifications** and **Trials** was  $F(1,16) = 8.640$ ,  $p = 0.010$ ,  $\eta^2 = 0.351$ . with means of **Pre-AM** ( $M = 3.933$ ,  $SE = 0.362$ ), **Pre-FM** ( $M = 3.329$ ,  $SE = 0.298$ ), **Transfer-AM** ( $M = 3.714$ ,  $SE = 0.308$ ) and **Transfer-FM** ( $M = 3.425$ ,  $SE = 0.258$ ).

Thus again there F4 shows the same pattern as F3.

#### For Right-Plus-Left - RPL:

**Sonification:** AM vs. FM,  $F(1,16) = 0.578$ ,  $p = 0.458$ ,  $\eta^2 = 0.035$ . With AM ( $M = 7.396$ ,  $SE = 0.622$ ) and FM ( $M = 7.174$ ,  $SE = 0.549$ ).

**Trials:** Pre vs. Transfer,  $F(1,16) = 7.327$ ,  $p = .016$ ,  $\eta^2 = 0.314$ . With **Pre** ( $M = 7.750$ ,  $SE = 0.651$ ) and **Transfer** ( $M = 6.820$ ,  $SE = 0.530$ ).

Interaction between **Sonifications** and **Trials** was,  $F(1,16) = 5.431$ ,  $p = 0.033$ ,  $\eta^2 = 0.253$ , with means of **Pre-AM** ( $M = 8.004$ ,  $SE = 0.707$ ), **Pre-FM** ( $M = 7.497$ ,  $SE = 0.636$ ), **Transfer-AM** ( $M = 6.789$ ,  $SE = 0.579$ ) and **Transfer-FM** ( $M = 6.851$ ,  $SE = 0.519$ ),

The RPL show the same pattern in Alpha EEG levels as F3 and F4, as there is no evidence of a difference between sonifications but there is a significant difference of both the Pre vs. Transfer trials and the Interaction.

#### Trial Pair 3: Trial 7 vs. Trial 8 - **Transfer** vs. **Post**

The third two-way repeated measures ANOVAs on the same measures was between the **Transfer** vs. **Post** trials i.e. trial 7 and trial 8. If the Alpha dropped on the right and increased on the left, between the **Transfer** vs. **Post**, this would be evidence of volitional control of the Alpha as it returns to base line.

None of the differences between sonifications or the Interactions effects showed a significant difference, but the Transfer vs. Post Alpha levels for both

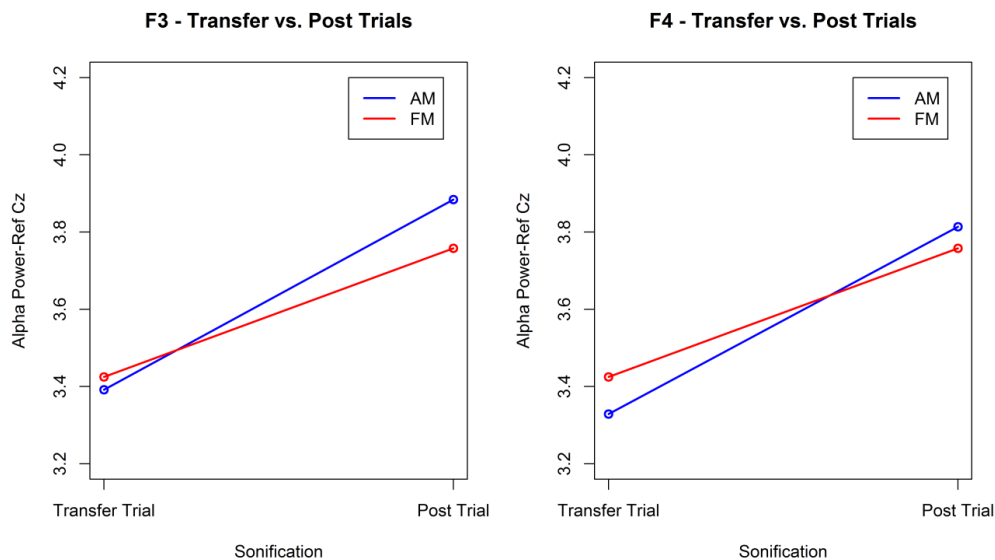
sonifications taken together showed a significant increase Transfer to Post for all three measures.

**F3:** Transfer vs. Post,  $F(1, 16) = 12.099$ ,  $p = 0.003$ ,  $\eta^2 = 0.431$ , with **Transfer** ( $M = 3.379$ ,  $SE = 0.263$ ) and **Post** ( $M = 3.800$ ,  $SE = 0.322$ ).

**F4:** Transfer vs. Post,  $F(1, 16) = 12.272$ ,  $p = 0.003$ ,  $\eta^2 = 0.434$ , with **Transfer** ( $M = 3.377$ ,  $SE = 0.268$ ) and **Post** ( $M = 3.786$ ,  $SE = 0.322$ ).

**RPL:** Transfer vs. Post,  $F(1, 16) = 12.191$ ,  $p = 0.003$ ,  $\eta^2 = 0.432$ , with **Transfer** ( $M = 6.820$ ,  $SE = 0.530$ ) and **Post** ( $M = 7.660$ ,  $SE = 0.648$ ).

Unfortunately as can clearly be seen in [Figure 6.5.2.7.2](#), because these patterns are the same on the left and right this merely indicates a return to the baseline Alpha levels and is not an interesting finding.



**Figure 6.5.2.7.2:** Left: Alpha levels for F3 in the Transfer trials and Post trial for the AM (blue) and FM (red). Right is the same for F4.

#### **Trial Pair 4:** Trial 2 vs. Trial 6 - **First** vs. **Last Training**

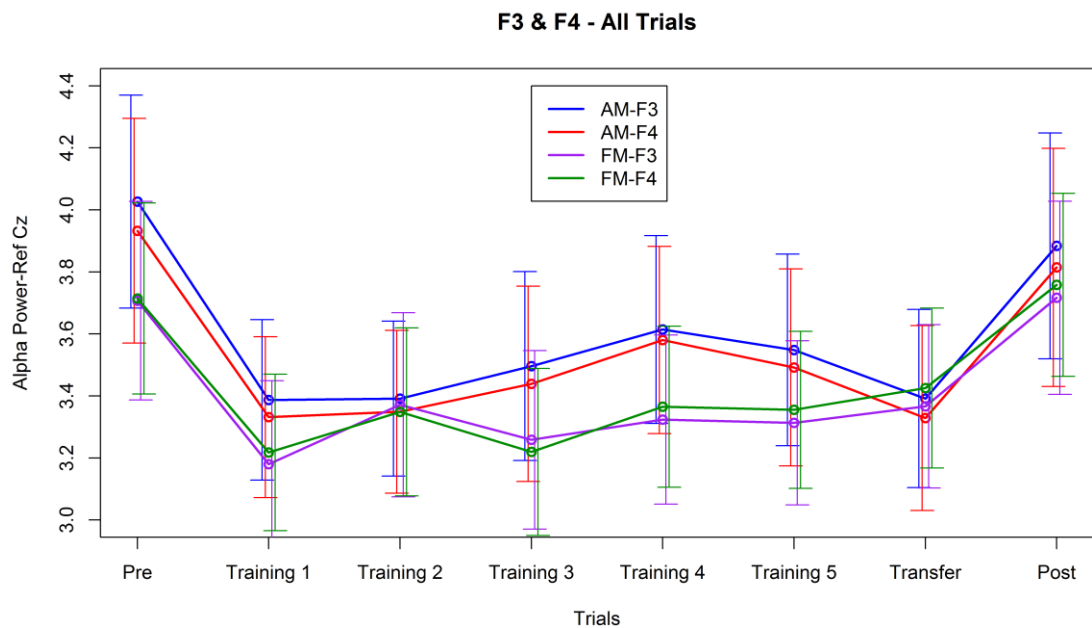
A two-way repeated measures ANOVA for Trial 2 vs. Trial 6 - First vs. Last Training trial, none of the measures had a significant value for the comparison between **Sonifications**, **Trials** or **Interaction** for the First vs. Last Training trial.

This suggests that despite any changes in the other trials, there was no statistically significant learning effect across training trials, but looking at [figure 6.5.2.7.3](#) below, there is a general suppression of all Alpha values from the baseline to the training and back up for the Post trials. This is probably due to an increase in attention during the training task, which is known to suppress Alpha, so is not particularly interesting. There is no statistically significant difference between F3 and F4 for any of the trials.

However, as can be seen in [figure 6.5.2.7.3](#) at base line the AM training group started with a higher Alpha and F3 was higher than F4 and the red and blue line stayed parallel across all trials, suggesting that at a group level, no change was made by the training. Whereas in the FM training the Alpha levels started with the same values between F3 and F4 but F4 (green line) was above the F3 (purple line) for most training trials. The FM training trials are pretty flat across the 5 trials, but there is an upward trend in the AM training trials.

Looking at the individual scores, for example in trial 5, 8 people had their right Alpha higher than left but 9 had the opposite and this is why the mean difference between F3 and F4 for the group is only ( $M=0.034$ ,  $SD=0.307$ ) for AM and ( $M=-0.041$ ,  $SD=0.238$ ) for FM, but if you take only the people that met the training criteria the numbers look a lot better with an AM of ( $M=0.293$ ,  $SD=0.267$ ) and FM of ( $M=0.216$ ,  $SD=0.147$ ). Thus, if around half the participants

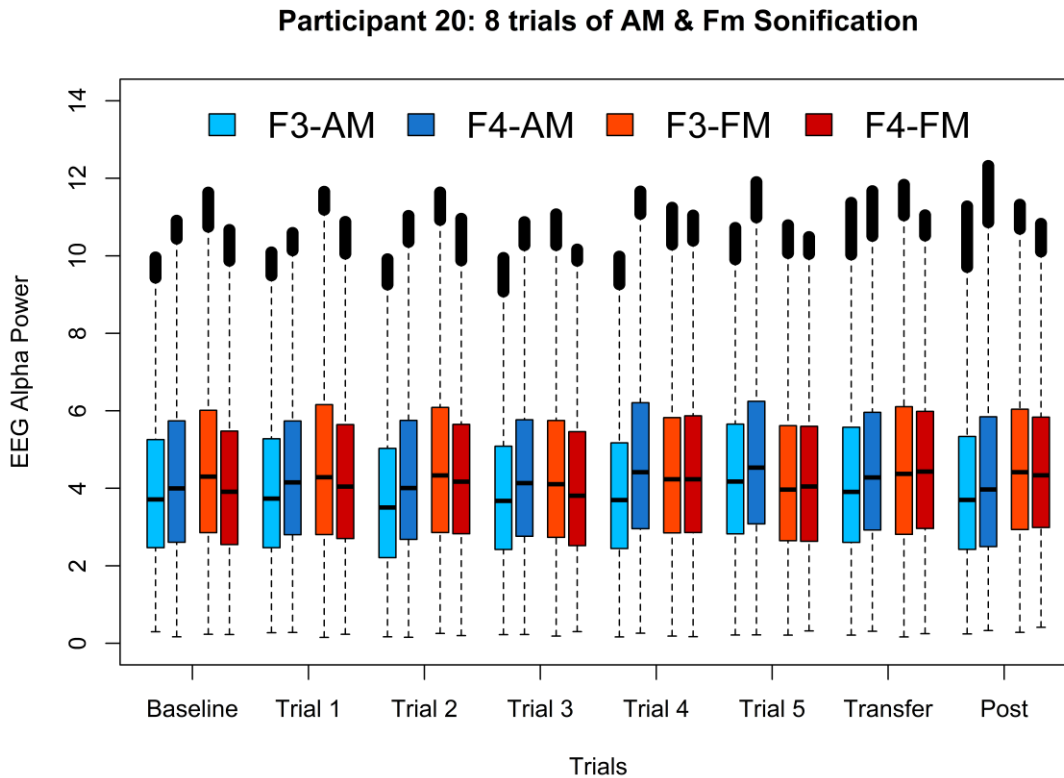
were 'responders', then the experiment should achieve a statistically significant effect by doubling the group size and excluding non-responders.



**Figure 6.5.2.7.3:** Group Means of Alpha of all 8 trials for the four different types of trial. The whiskers show 'standard error'.

The example in [figure 6.5.2.7.4](#) shows a person who can raise their Alpha on the right and lower it on the left and in this case the FM sonification starting with Alpha higher on the left and becoming nearly equal by the end. But of course this is the average of one person so each bar is one 200 seconds trial of data and this pattern does not show at a group level.





**Figure 6.5.2.7.4:** Is for participant 02: Mean of Alpha of all 8 trials for AM and FM for F3 and F4. Blue bars are F3 and red is F4. The first blue and red bars on the left are from the AM trials and the darker blue and red bars, on the right are of the FM trials.

#### 6.5.2.8. Summary of the EEG Analysis

Thus to summarise the findings for the EEG analysis, gender did not have an effect on the Alpha levels. The order which the participants did the sonification did not make a difference to the Alpha levels when the sessions were a week or more apart. By scheduling the sessions for the same time of day, this did seem to control for the circadian rhythm, known to affect Alpha levels, as the baseline values were not statistically different between sessions.

The asymmetry measure of FAA, Log-FAA and the RPL did not provide any more useful information above the original data of F3 and F4.

There was no Pre vs. Post difference in Alpha EEG levels and no sign of learning as there was no difference in the First vs. Last Training trials. There was a statistically significant difference between Pre vs. Transfer and Transfer vs. Post trials for all three measures of F3, F4 and RPL, However as seen in [figure 6.5.2.7.3](#) this merely reflects a reduction in Alpha from baseline to the training trials, which is probably due to increased attention during the task and then a return to the baseline levels in the post recording. Furthermore the first training trial (Trial 2) and the Transfer trial (Trial 7) had the two lowest Alpha levels, which is support for the idea that it is the attention to the task that is suppressing the Alpha. This means the Transfer trials may not be a useful measure when training to enhance Alpha brain waves as it is confounded by attention.

There was no difference in Alpha EEG levels between any of the AM and FM sonification training trials. There was a smattering of interaction effects but there was no consistent difference between the two sonification techniques in any of the trials for any of the measures.

The lack of a control group does make it more difficult to assess if any of the changes seen in this experiment are real or useful, but this is inevitable, as this research does not have baseline data of an EEG sonification that has a 'known' and definitive effect in real-time neurofeedback. Furthermore it was considered unethical to put people through a sham or fake Intervention that was known not to work, when it was unknown if the real intervention would succeed.

### 6.5.3. Measures 3: NASA-TLX

After each tracking trial, and after the training trials, participants were asked to fill in the same NASA Task Load Index questionnaire (NASA-TLX) that has been used in the previous two experiments. They were asked to rate how hard they found the tracking task on 6 factors of, Mental Demand, Physical Demand, Temporal Demand, and, how much Effort, Frustration and how good they thought their Performance was. For example the Mental Demand question was:

#### Mental Demand

"How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?"

The 6 questions were presented in a random order and participants used a mouse to move a slider on the computer screen (See [figure 4.3.4 in Chapter 4](#)). The scale was from "low" on the left with a score of 1 to "high" on the right with a score of 20. After filling in the NASA-TLX for the first tracking trial there was a pause screen so the participants could have a rest before clicking to do the next tracking task. After the NASA-TLX for the second tracking trial, the Mood questionnaire was presented as the Pre-Mood questionnaire for the training session. Then after the training the NASA-TLX was given a third time followed by the post Mood questionnaire.

Three sets of analysis were conducted on the 6 questions of the NASA-TLX:

**Tracking: NASA-TLX Analysis:** (see [section 6.5.3.1](#))

<b>Order:</b>	<b>AM</b> Trials First vs. <b>FM</b> Trials First
<b>Gender:</b>	<b>Female</b> vs. <b>Male</b>
<b>Sonification:</b>	<b>AM</b> vs. <b>FM</b>
<b>Tracking:</b>	<b>Pan</b> vs. <b>Vertical</b>

**Training: NASA-TLX Analysis:** (see [section 6.5.3.2](#))

<b>Order:</b>	<b>AM</b> Trials First vs. <b>FM</b> Trials First
<b>Gender:</b>	<b>Female</b> vs. <b>Male</b>
<b>Sonification:</b>	<b>AM</b> vs. <b>FM</b>

### 6.5.3.1. Tracking: NASA-TLX Analysis

**Order:** An independent-sample two-sided t-test of NASA scores (DV) by order (IV) of the tracking trials '**Pan First**' vs. '**Vertical First**' and for the post training '**AM First**' vs. '**FM First**', found only the 'Frustration' question in the '**Pan First**' trial showed any differences in the scores by order with  $t(15) = -2.518$ ,  $p = 0.024$ , the 8 people that did the Pan trial first scoring ( $M=6.38$ ,  $SE=3.335$ ) and the 9 people that did the vertical first scoring ( $M=11.22$ ,  $SE=4.438$ ). Given that this is only one out of 18 T-Tests, this is not considered significant, thus the participants will be grouped by Pan and Vertical, for subsequent analysis.

**Gender:** An independent-sample two-sided t-test of NASA scores (DV) by gender (IV) found no difference, thus again gender was collapsed across groups.

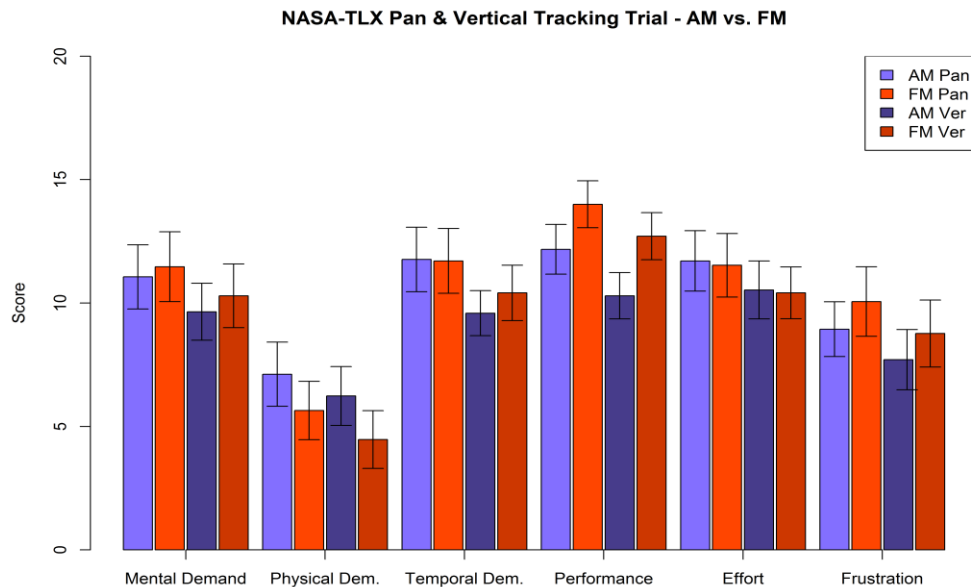
**Sonification:** A within-subject 'repeated measures' ANOVA of the "NASA" scores (DV) for 'Sonification' (AM vs. FM) by 'Tracking' (Pan vs. Vertical) (IVs), did not show a within-subject effect for all questions grouped together for the Sonification or Tracking.

For the **Performance** question there was a difference between **AM** and **FM** with Greenhouse-Geisser corrected  $F(1,16) = 4.415$ ,  $p = 0.052$ .  $\eta^2 = 0.216$ , with AM of ( $M=11.235$ ,  $SE=0.777$ ) and FM of ( $M=13.353$ ,  $SE=0.888$ ). So people were rating their performance as better with FM for both the Pan and Vertical trials and sonification accounted for around 22% of the variance within the group.

**Tracking:** For the 'Performance' question there was a difference between **Pan** and **Vertical** tracking with  $F(1,16) = 6.686$ ,  $p = 0.020$ .  $\eta^2 = 0.295$ , with the **Pan** tracking trial scoring ( $M=13.088$ ,  $SE=0.729$ ) and the **Vertical** tracking trial scoring ( $M=11.500$ ,  $SE=0.735$ ). So as expected, regardless of the sonification, the Pan tracking trial was rated as having a better performance.

For the 'Physical Demand' question there was a difference between **Pan** and **Vertical** tracking with  $F(1,16) = 4.418$ ,  $p = 0.052$ .  $\eta^2 = 0.216$ , with the **Pan** tracking trial scoring ( $M=6.382$ ,  $SE=1.055$ ) and the **Vertical** tracking trial scoring ( $M=5.353$ ,  $SE=1.046$ ). Thus the Panning trial was found to take more 'Physical Demand' than the Vertical tracking trial.

None of the interactions between 'Sonification' and 'Tracking' were found to be significant.



**Figure 6.5.3.1:** Shows the mean and standard error of the NASA-TLX self-rating scores for the four tracking trials. Purple is the AM trials and Orange is the FM, the lighter colours on the left are the 'Panning' trials and the darker on the right are the 'Vertical' trials. There is a statistically significant difference between AM and FM as well as between the 'Pan' and 'vertical' tracking trials for the 'Performance' question.

In summary as seen in **Figure 6.5.3.1** the 'Panning' trial was had higher scores for 'Physical Demand' but people rated their 'Performance' as better in the 'Panning' trials.

The FM sonification was rated as giving a better 'Performance'.

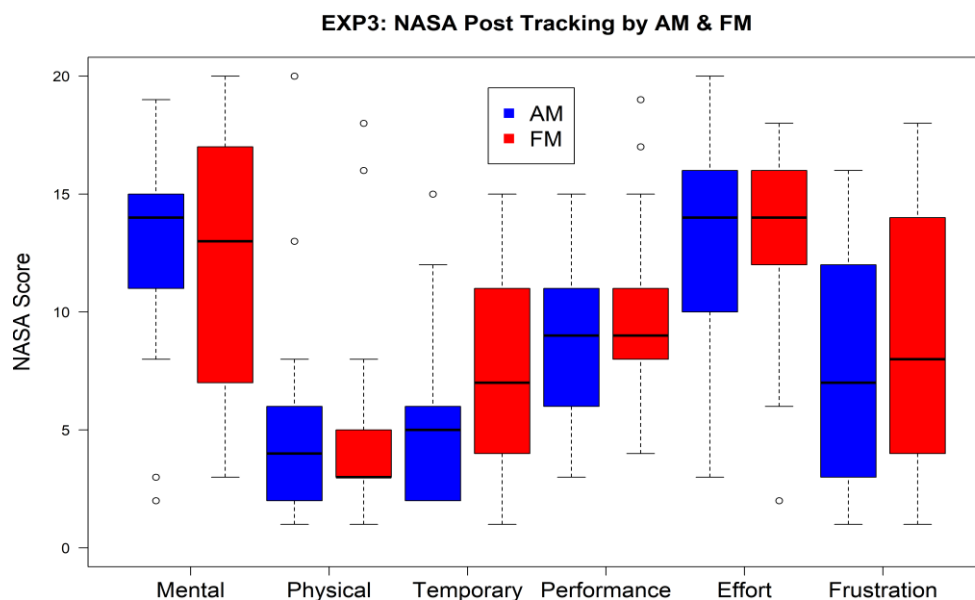
This is somewhat surprising as it might be argued that Panning of the AM sonification was more congruent to the task and that the vertical tracking of the FM sonification would require more mental effort.

### 6.5.3.2. Training: NASA-TLX Analysis

**Order:** An independent-sample two-tailed t-test of NASA scores (DV) by order (IV) of sonification showed no differences thus presentation order will be ignored in subsequent analysis.

**Gender:** a second independent-sample two-sided t-test of NASA scores (DV) by gender (IV) found only one question was different between genders with the 8 females finding the training session less Frustrating ( $M=5.13$ ,  $SE=2.900$ ) than the 9 Males ( $M=10.00$ ,  $SE=5.545$ ) and  $t(15) = -2.225$ ,  $p = 0.039$  (with Equal variances not assumed). Thus again gender will be collapsed across groups.

**Sonification:** A within-subject 'repeated measures' ANOVA of the "NASA" scores (DV) for 'Sonification' (AM vs. FM), did not show any within-subject effect between Sonifications.



**Figure 6.5.3.2:** Box-&-Whisker plot show the Median and quartiles of the NASA-TLX self-rating scores for the **AM** (blue) and **FM** (red) for the 'Training' Trials. (The

*open circles are outliers, i.e. 1.5 times smaller or larger than the interquartile range from the first or third quartile).*

These findings are a little surprising, as the comments from the participants after the experiment suggested that many of them had a sense of control, and despite the irritation of the sound, the FM sonification was self-rated as supporting better performance. Although not statistically significant [figure 6.5.3.2](#), shows that the FM training trials are generally rated as more mentally demanding and taking more 'Effort' and being more 'Frustrating' than AM but giving a better performance.

**NASA-TLX Summary:** The NASA Task Load Index questionnaire had two main parts, the Task Load of the '**Tracking**' task and the Task Load of the '**Training**' task.

In the '**Tracking**' task people rated their **performance** as better in the FM tracking task in both the Pan and Vertical trials. They also thought their performance was better on the **Pan** tracking trial, despite finding it more of a '**Physical Demand**' than the Vertical trials.

For the '**Training**' trials the NASA-TLX did not show any statistically significant differences between the sonifications. However there was a trend for the FM training trials to be generally rated as more mentally demanding and taking more 'Effort' and being more 'Frustrating' but giving a better performance than the AM training.



#### 6.5.4. Measures 4: Emotional Scale

After the tracking tasks, before the training, the 'Pre' Mood questionnaire was administered using the PsychoPy software and then again after the training. Participants were asked to rate "how you feel RIGHT NOW" on 9 different questions: Excited, Happy, Calm, Lethargic, Depressed, Miserable, Tense, Energetic and Overall mood.

Just as in the previous experiments, the questions were presented in a random order, on a computer screen with a horizontal slider which ranged from "Low" on the left, that scored 1, to "High" on the right which scored 20 (See [Section 5.3.5.1](#), for more explanation of the task and rationale).

##### Emotional Scale Analysis:

**Mood: By Order:** An independent-sample two-tailed t-test of Mood scores (DV) by order (IV) of which sonification was done first, showed only the Post FM trial was different on the '**Lethargic**' question, with the 9 people that started with 'AM-First' trials scoring ( $M=13$ ,  $SE=5.025$ ) and the 8 who started with 'FM-First' scoring, ( $M=6.50$ ,  $SE=5.372$ ) and  $t(15)= 2.578$ ,  $p = 0.02$ . So the FM training was rated as making people more 'Lethargic' if they started with the AM training followed by FM. Again as this is only one out of 36 T-Tests, the order of presentation will be ignored in subsequent analysis.

**Mood: By Gender:** a second independent-sample two- tailed t-test of Mood scores (DV) by gender (IV) found a 'Post FM' difference between gender, again on the '**Lethargic**' question, with the 8 'Females' scoring ( $M=13.13$ ,  $SE=5.718$ ) and the 9 'Males' scoring, ( $M=7.11$ ,  $SE=5.011$ ) and  $t(15)= 2.312$ ,  $p = 0.035$ . Also on the '**Calm**' question, 'Post AM' the females scored ( $M=17.38$ ,

SE=1.506) and 'Males' scored, (M=**14.78**, SE=2.991) and  $t(15) = 2.214$ ,  $p = \mathbf{0.043}$ .

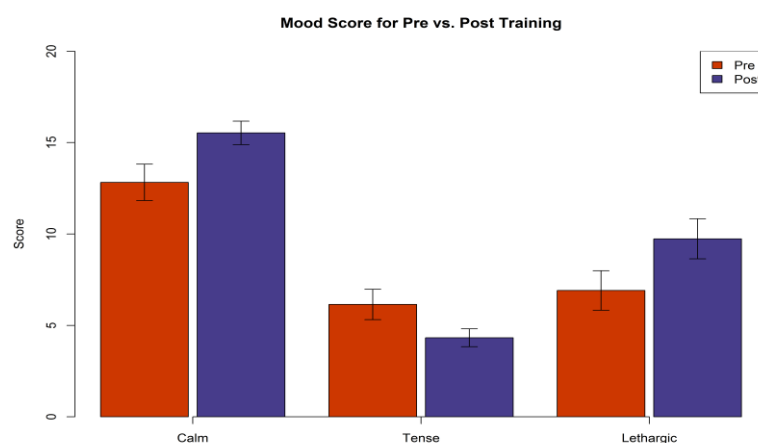
So females were feeling more 'Lethargic' after the FM training and more 'Calm' after the AM training than the males. Thus Gender will be collapsed across groups for subsequent analysis.

**Mood: By Sonification:** A within-subject 'repeated measures' ANOVA of the 'Mood' scores (DV) by 'Sonification' (AM vs. FM) and 'Pre vs. Post' (Figure 6.5.4.2) did not show any within-subject effect between sonifications,

but did show a number of statistically significant differences between 'Pre' vs. 'Post' trials. As seen in Figure 6.5.4.1, for the 'Calm' question the results were  $F(1,16) = 8.474$ ,  $p = \mathbf{0.010}$ .  $\eta^2 = 0.346$ , with a 'Pre' score of (M= **12.824**, SE= 0.995) and a 'Post' of (M= **15.529**, SE= 0.644).

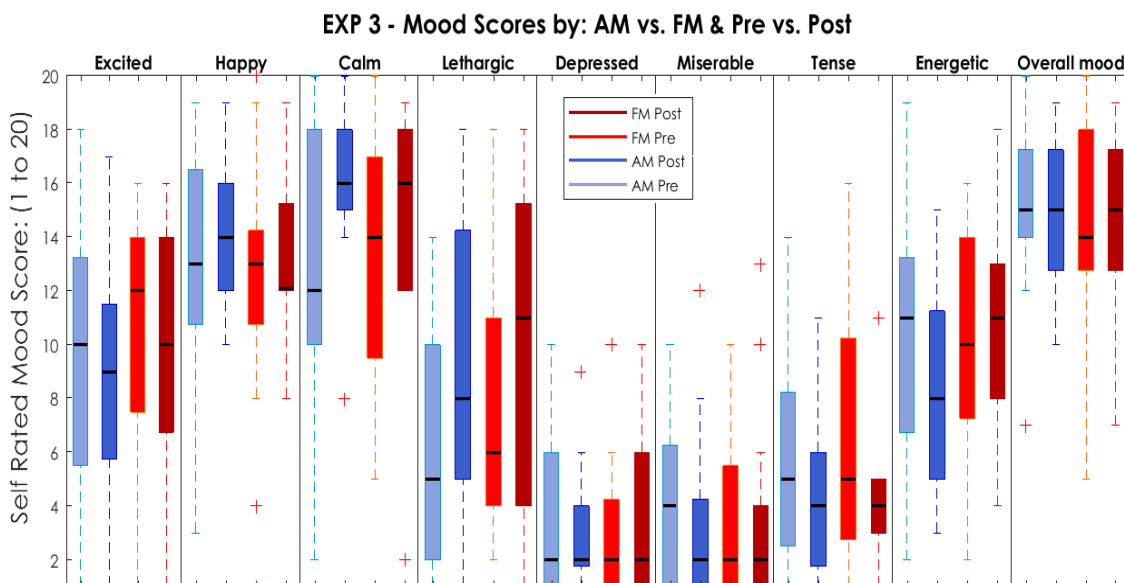
For the 'Tense' question the results were  $F(1,16) = 5.516$ ,  $p = \mathbf{0.032}$ .  $\eta^2 = 0.256$ , with the 'Pre' (M= **6.147**, SE= 0.829) and the 'Post' of (M= **4.324**, SE= 0.491).

For the 'Lethargic' question  $F(1,16) = 5.714$ ,  $p = \mathbf{0.029}$ .  $\eta^2 = 0.263$ , with the 'Pre' (M= **6.912**, SE= 1.081) and the 'Post' of (M= **9.735**, SE= 1.097).



**Figure 6.5.4.1:** Bar plot of the mean and standard error bars of the '**Pre**' (Orange) and '**Post**' (Purple) or three Mood questions with significant differences, Calm, Tense and Lethargic.

Thus, as seen in **Figure 6.5.4.2**, for both **AM** and **FM** sonification neurofeedback sessions taken together from the '**Pre**' to '**Post**', people tended to increase their Calmness and Lethargic score and decrease their Tense score with training.



**Figure 6.5.4.2:** Box-&-Whisker plot shows the median and quartiles of the Mood self-rating scores for the four types of trials: **AM-Pre**, **AM-Post** and **FM-Pre**, **FM-Post** for all 9 questions.

Furthermore as seen in **Figure 6.5.4.2** (which is showing the mediums), there was also an Interaction between **AM** and **FM** and **Pre** and **Post** for the **Energetic** question with a Greenhouse-Geisser of  $F(1,16) = 7.785$ ,  $p = \mathbf{0.013}$ .  $\eta^2 = 0.327$ , The

'AM Pre' scored (Mean= **10.529**, SE= 1.138), and the 'AM Post' only scored (Mean= **8.471**, SE=.982) but for the 'FM Pre' training the rating was (Mean= **10.235**, SE= 1.020) and the FM Post was (Mean= **10.941**, SE= 1.024).

Thus the Interaction between **AM** and **FM** with the **Pre** and **Post** training showed that, in the AM training people's '**Energetic**' scores dropped but in the FM training they went up. This is similar to experiment 2, the '**Energetic**' scores moved in the desired direction for FM but not for the AM sonification.

**Summary of Mood Scale:** The Mood Scale was administered pre and post of the training trials and there were three main findings. Participants' self-rating scores between 'Pre' and 'Post' went up for '**Calmness**' and '**Lethargic**' but decreased on the '**Tense**' scale for both sonifications. Also there was an Interaction between **AM** and **FM** sonifications and '**Pre**' and '**Post**' time points, on the '**Energetic**' question, such that in the AM training, peoples 'Energetic' scores dropped but in the FM training they went up.

## 6.6. Discussion

This experiment was designed to test if two channels of Frontal Alpha EEG could be sonified in a manner that could help people learn to train their own brainwaves by hearing them in real-time.

This experiment combined an assessment of people's ability to perceive some aspect or aspects of EEG activity in a sonification and their ability to simultaneously rate their response in real-time with a slider. One motivation was

that if a quick and simple assessment method could be developed based on these ideas, this could allow rapid testing of candidate sonifications, thus avoiding or limiting the need for costly and time consuming randomised controlled neurofeedback studies.

Given that there is no current 'ground truth' of an optimal sonification for EEG presentation for any new sonification mapping to be measured against, two different sonification techniques were compared against each other on the tracking and training tasks, to identify their relative merits.

Two conceptually and technically simple sonification techniques that are capable of real-time sonification were selected, in order to minimise the number of subjective design decisions needed in order to establish a suitable baseline.

An attempt was made to make both the Amplitude and Frequency Modulation Sonification perceptually equivalent (in terms of available resolution and range though not necessarily in other respects), by matching the number of just noticeable differences across the amplitude range of EEG data and mapping the amplitude and frequency increments to the perceptual Log scale.

The two sonifications were assessed on four measures. Two of these measures were quantitative: the tracking accuracy, and the physiological measure of the participants Alpha EEG. The other two measures were qualitative; the NASA-TLX task load index and the Mood assessment.

The tracking accuracy was disappointingly low, with a grand mean of 0.309 and a range from 0.076 to 0.548, despite adding a physical slider. This is

probably due to the increased complexity of adding a second auditory stream to the task.

In the piloting phase, one design issue that had emerged was whether or not to give an explicit instruction to the participants on how to track the sonification. Considering the results, the difference between the two tracking tasks suggests how important the instructions are, with the 'Vertical' tracking having a higher mean but also getting 70% of the top half of the highest scores. Contrary to predictions the 'Panning' did not get a significantly better tracking accuracy for the AM sonification.

The tracking accuracy score may seem low, but Cohen (1969, p23) gives an interesting example where a 0.2 correlation is 'real' with humans in the real world. (In New York, there is a 0.2 correlation between the heights of 15 and 16 year old girls, but a 0.5 correlation between 14 to 18 year olds, and 0.8 between 13 to 18 year olds girls). So these tracking accuracy correlations although low, could still prove a useful tool for distinguishing between sonifications.

Furthermore, the reality is that the fluctuations in the EEG signal are very rapid, but smoothing or averaging the signal to make it more 'trackable' would contradict the purpose of the tracking task, since part of the point of the experiment generally is to assess the ability of sonifications to communicate the fine grained temporal character of real-time EEG signals for neurofeedback purposes.

There were some statistically significant differences in the Alpha EEG values in the training sessions, but when looking across all eight trials at a group level these reflect the large drop in Alpha power from the 'Pre' baseline trial to the

training trials and the return in Alpha levels from the training trials to the 'Post' training recording. (See [Figure 6.5.2.7.3](#))

So the question is, as there was no difference between the two sonifications, were they both equally as bad or both equally as good? There was an increase in calmness and lethargy and a decrease of tension in the training but, without a control group, given that there is no difference found in this experiment between the sonifications in the Alpha EEG, this is possibly due to sitting still with their eyes closed for 20 minutes.

## Chapter 7: Conclusions

Summary At the outset of this research it had been the intention to design many exciting new sonification techniques for the presentation of real-time EEG that would be appropriate for neurofeedback. But it quickly became apparent from the literature review that very little of the basic foundational work needed for a research discipline had been done.

Therefore, as there did not appear to be data to give a 'ground truth' or empirical evidence to establish a baseline for how well the real-time EEG could be presented with sound, which any new sonification could be compared against, it was felt necessary to start with the basics and select two comparatively simple sonification techniques to conduct a head-to-head comparison and develop a test battery that could provide a quantitative assessment of their relative abilities to convey the real-time EEG data. After all it is quick and relatively simple to create a complex sonification mapping that appears useful but it is the validation of the sonification that makes it a research project as opposed to an art project.

### 7.1. Outcomes & Implications

This dissertation has presented a series of three experiments that have tried to assess how well a sonification can convey real-time EEG data. In order to establish a baseline, two deliberately simple sonification techniques were selected and used in all three experiments, **Amplitude Modulation** (AM) and **Frequency Modulation** (FM).



The first and second experiments used a single channel of EEG to generate a single channel of sound and the third used two channels of EEG for two channels of sound.

The first experiment used a tracking task, where the participant heard a pre-recorded EEG sonification and tried to track the activity they could hear with a slider. The second experiment used a training task, where the participant heard a real-time sonification of their own EEG and tried to modify their physiology to alter the sound of the sonification.

The third experiment was both a consolidation and extension of the previous two studies and combined both a tracking and training task for two new two channel versions of the AM and FM sonification methods, with two sessions for each participant, one for each sonification method.

Taking all three experiments together, head-to-head comparisons were made of two different sonification techniques on the tracking and training tasks for both 1 and 2 channels of EEG, with task load measures (measures of effort) for all.

**Table 7.1.1** shows the three experiments with the number of sessions each participant carried out, the number of EEG channels, the type of sonification, the type of task, and the number of trials in each session.

Experiment	Sessions	Channels	Sonification	Task	Trials & Timings
EXP 1	1	1	AM	Tracking	4 X 1 minute
			FM	Tracking	4 X 1 minute
EXP 2	1	1	AM	Training	3 X 3 minutes
			FM	Training	3 X 3 minutes
EXP 3	2	2	AM	Tracking	2 X 1 minute
				Training	5 X 4 minute
			FM	Tracking	2 X 1 minutes
				Training	5 X 4 minutes

**Table 7.1.1:** Shows the number of sessions per participant in each of the three experiments, how many channels of EEG were used and the number and duration of trials in each session.

By comparing the: (i) **Tracking** vs. **Training** and (ii) **1 channel** vs. **2 channels** of EEG for both **AM** vs. **FM** sonification techniques, this allowed 'triangulation' in assessing the relative merits of the sonifications.

For example; one sonification could have been better on all factors, i.e. better tracking scores and better learning outcome in the training for both 1 and 2 channel of EEG. Then this would be a quite clear-cut result suggesting this was a better sonification. Alternatively, one sonification technique may be better for the tracking trials and the other for training trials, or similarly, one sonification may be better at conveying one channel of EEG but the other at two channels of EEG.

Consequently, a combination of quantitative and qualitative assessment tools was used across all three experiments in order to assess the relative merits of the sonifications and try to establish if they have any utility for neurofeedback.

#### **7.1.1. Sonification Techniques**

The AM and FM sonification techniques were chosen because they are simple to make and conceptually relatively simple, they are perhaps the most basic sonification techniques capable of conveying real-time EEG data. In this sense they make a suitable starting point for creating a baseline that future work can build on. Also they have been widely used in the general sonification field, so there is some research to validate the utility in other contexts.

In experiment 1 and 2, the AM and FM sonification techniques mapped the Alpha EEG 'input' signal to a comfortable amplitude and frequency 'output' range that was experimentally derived in the piloting process. However in experiment 3, it was felt in order to make a comparison between the two sonification techniques fairer and more scientifically valid, a more rigorous attempt was made to make them perceptually equivalent in relevant respects. Thus all three experiments used the same two types of sonification techniques in order to establish a baseline with the capacity for subsequent research to build on with newer and more complex sonification techniques.

#### **7.1.2. EEG Parameter**

An important issue was the selection of the EEG parameter to be sonified. The alpha EEG band was chosen in this research because it typically has a larger

amplitude in relation to the other EEG bands (See [section 2.1.9](#)), which makes it easy to measure. It is also a well-known component with known physiological and psychological concomitants that can be modified with training. Furthermore, the alpha band has interesting temporal dynamics with prominent activity in the decasecond time range, which should be suitable for sonification. Also, because the alpha band is associated with relaxation, it is considered one of the safest EEG bands to train (See [2.1.9](#)), as training that unintentionally increases the alpha levels excessively is merely likely to make people sleepy. For two-channel training, the frontal alpha symmetry index (see [section 2.1.10](#)) again is a relatively well-known EEG parameter with decades of research. It is safe if trained in the correct direction (i.e. an increase in amplitude on the right and/or a decrease on the left) and has known psychological properties. This makes the alpha EEG band suitable for sonification and neurofeedback training, as well as being appropriate to be used with a non-clinical participant population.

### **7.1.3. One vs. Two Channel Sonification**

As was noted at the beginning of this dissertation, one of the primary motivations for use of sonification for neurofeedback is its potential for conveying multiple simultaneous streams of data in a manner that can readily be perceived by the user. Therefore it was decided to compare one and two-channel sonifications on both the tracking and training assessments. Hence, experiment 1 and 2 used one-channel sonifications and experiment 3 investigated two-channel sonifications. Future studies are intended to extend the number of channels, potentially to as many as 57 channels, i.e. three EEG frequency bands for each of the 19 channels in a typical 'full cap' EEG

recording. Although at first this may appear as an unintelligible amount of individual data streams to monitor or comprehend, just as when listening to an orchestra with as many as 50 musicians, it is the synthesis of all individual activity that creates the overall timbre. Similarly, an electrode at a particular location on the scalp will measure the sum of activity across the brain, but generally it is not the electrical activity measured from a particular electrode that is of interest, but the inferred activity of the brain regions that generates the electrical activity.

For example in experiment 3, it was hoped that having two channels of sonification from the left and right frontal cortex the synchronised activity of the frontal alpha symmetry would be perceived as one stream of activity rather than two individual sound sources.

#### 7.1.4. Assessing Temporal Resolution and Dynamics

One of the most critical aspects in the conditioning theory that underpins neurofeedback is the speed of feedback and the **temporal resolution** of the feedback, i.e. how accurately the variations in a signal can be measured and how quickly the feedback can be given. Furthermore one of the most prominent features of the real-time EEG data stream is its **temporal dynamics**, i.e. the complexity and speed of the EEG fluctuations over time. Thus the explicit decision was taken to minimise any temporal averaging of the EEG signal in order that the full temporal dynamics of the EEG signal could be converted into sound.

Accordingly, any attempt to measure how well a sonification can convey the EEG data must be able to capture both the temporal resolution and temporal

dynamics of the data transformation. As discussed in [section 1.2.3.2](#) and [1.2.3.3](#), this is an area where sonification has a lot of potential to convey the temporal complexity of the real-time EEG data stream but as also discussed in [section 3.6](#) of the literature review, there is a very limited range of assessment tools that can capture the temporal dynamics of an EEG sonification session.

Therefore the tracking task was an attempt to capture how well people can perceive the activity of an EEG signal using sonification. The 'Temporal Onset Detection' task (See [section 3.6.3](#)) can potentially capture a rudimentary aspect of the temporal resolution of a sonification by getting participants to push a button when they hear the onset of a sound but this is hardly the same as the perceptual task of continually following a rapidly fluctuating signal over several minutes. So despite the obvious shortcomings of physically tracking such a rapid sound with a slider, any delays that this would produce would affect both sonification techniques equally and enabled some degree of assessment of the information transfer from the EEG signal to the participant's perception. The decision not to smooth or average the data may make the assessment task more difficult but will hopefully allow the true nature of the EEG signal to be conveyed.

Two potentially significant shortcomings of the tracking task as an assessment tool are, firstly, the issue of multiple streams of information. It may well be possible for the majority of people to simultaneously monitor multiple streams of data either visual or auditory and bring their attention to bear on whichever stream was most salient at any given time or even perceive the multiple streams as one signal. But what is less likely is that people could physically track multiple data streams with multiple sliders. Thus in order to try and establish if

people perceive a single stream of activity from multiple streams of sonification and therefore if the tracking task has any utility for more than one sound channel, experiment 3 used two channels of EEG to give two channels of sonification, one in each ear and the tracking task was run twice with two different instructions.

One instruction emphasised the *difference* between the two sound tracks, by asking people to assess which side was either 'louder' or had a higher 'frequency' and to move the slider in that direction, this was called the panning trial. The other tracking instruction emphasised the *sum* of the two channels, by asking people to track the combined output of the two channels (see [section: 6.5.1 Tracking](#)).

A second possible shortcoming of the tracking task that may not affect the 'Two-alternative Forced-Choice' method or the real-time neurofeedback training is the difference between explicit vs. implicit perception. Although the tracking task does escape from the reliance on subjective rating scales, there may be subtleties in the complexity of the signal that participants can perceive but not be consciously aware of or consciously report on. As mentioned in [section 2.3.7](#) on 'Cognitive Load Theory', when presented with a complex task people tend to rely on schemas that they may not consciously be aware of. Thus, asking their opinion after the task or getting them to explicitly track a signal may not reveal this implicit perception particularly in a more demanding task like the two-channel tracking.

This is partly why the tracking task is only envisaged as an initial comparative assessment of the relative merits of a particular sonification and any new sonification technique that was selected by the tracking task, would have to

be validated in a more rigorous real-time EEG sonification neurofeedback experiment.

#### 7.1.5. Overall Results

Taking the three experiments together, that combine quantitative and qualitative assessment tools for both tracking and training tasks with both one and two-channel and AM and FM sonification techniques, [Table 7.1.5.1](#) shows the within and between subject comparisons that are possible for these measures.

		AM		FM	
1 channel	Track	EXP 1 (N.17)	← within subject →	EXP 1 (N.17)	↕ between subject
	Train	EXP 2 (N.20)	← within subject →	EXP 2 (N.20)	
2 channel	Track	EXP 3 (N.17)	← within subject →	EXP 3 (N.17)	↕ within subject
	Train	EXP 3 (N.17)	← within subject →	EXP 3 (N.17)	

**Table 7.2.5.1:** Shows how when the three experiments are taken together this allows **within** and **between subject** comparisons between the **tracking** and **training** trials for both **AM** and **FM** sonifications and for both **1** and **2** channels of EEG and in the brackets is the number of participants in each group.

The main results of these three experiments are summarised in [table 7.1.5.2](#) and give a bit of a mixed outcome. The four main outcome measures of these experiments are Tracking-Accuracy scores, EEG Alpha levels and Mood changes in the training task and the NASA-TLX task load index for both the Tracking and training tasks.



Experiment	Results	Type of Measure
<b>EXP 1: Track-Accuracy</b>	<b>FM (0.214) better</b> than AM (0.134)	Quantitative
<b>EXP 1: Track-NASA-TLX</b>	<b>AM easier</b> than FM	Qualitative
<b>EXP 2: Train-EEG</b>	No Change - No significant difference between AM & FM	Quantitative
<b>EXP 2: Train-NASA-TLX</b>	<b>AM easier</b> than FM	Qualitative
<b>EXP 2: Train-Mood</b>	<b>Correct Pre to Post Change - FM better</b> than AM	Qualitative
<b>EXP 3: Track-Accuracy</b>	No significant difference between FM (0.309) & AM (0.309)	Quantitative
<b>EXP 3: Track-NASA-TLX</b>	<b>FM better</b> than AM	Qualitative
<b>EXP 3: Train-EEG</b>	No Change - No significant difference between AM & FM	Quantitative
<b>EXP 3: Train-NASA-TLX</b>	No significant difference between AM & FM	Qualitative
<b>EXP 3: Train-Mood</b>	<b>Correct Pre/ Post Change</b> - No significant difference between AM & FM	Qualitative

**Table 7.2.5.2:** Shows the main results of the three experiments. The numbers in the brackets represent the mean tracking accuracy for each sonification.

**Training:** The most disappointing finding for this research is that neither of the training experiments produced changes in the EEG parameters, despite evidence from the literature suggesting that a single session of neurofeedback training could be sufficient to produce a change and despite improvements in the associated mood in the predicted direction. Of course it must be remembered the participants were not from a stressed or depressed population so were less likely to benefit from alpha training and there was only one session for each sonification.

There are a number of other factors that may account for lack of change in the EEG but as discussed in chapter 3 on the literature, very few of the EEG sonification neurofeedback papers provided sufficient details of the study design to draw any solid conclusions about what was different in the current experiments.

Thus until a sonification technique is found that can be shown to change the EEG in a single session using the current experimental protocol. It is difficult to know whether it is the sonification techniques or the research protocol that is responsible.

But still, this does raise the question, if a single session of Alpha EEG sonification neurofeedback failed to show a change in EEG parameters, was it the sonifications, the EEG parameter, the outcome measures, the duration or number of sessions, the number of participants, or the concept of neurofeedback that was at fault?

Is the fact that the mood has changed in the predicted direction an indicator that the neurofeedback worked but that current EEG analysis methods are too coarse to identify the changes that were there?

In keeping with the premise of this dissertation, it could be argued the human auditory system is able to perceive details in the real-time sonified EEG data that current EEG analysis is unable to measure, for example; the use of temporal averaging over several seconds to calculate power will lose a lot of information about the temporal dynamics of the signal, although clearly this is an interpretation that would remain speculative without a lot more evidence.

So various questions arise:

- (i) are more sessions required in order to show a change in the EEG?
- (ii) are better sonifications needed?
- (iii) should a clinical population that would more likely to find the alpha training more useful be studied?
- (iv) would better EEG analysis, that takes into account the full temporal dynamics of the EEG signal, be able to pick up the subtle changes in the training data?

Thus all that can be reasonably concluded from the three experiments about the sonification techniques is that they both show promise for neurofeedback and that both one and two-channel sonifications could be useful. Furthermore FM sonification may well be better than AM at conveying real-time Alpha EEG data.

**Tracking:** Turning to the tracking task, for the single-channel sonification the tracking accuracy scores showed FM to be better. However, unexpectedly there was no difference in tracking accuracy scores between the AM and FM sonification techniques for the two-channel sonification for either of the two different slider orientations. There was, however, a statistically significant difference associated with the two slider orientations themselves, with the vertical trials scoring higher tracking accuracy. Not only does this highlight the importance of the orientations and their associated instructions in the tracking task, but the fact that the mood did change in the predicted directions in the training trials, shows that the two channels sonification does 'work' to some extent. However, as there was no difference between the two sonification techniques in either the tracking task or with the EEG in the training task, this is a

problematic finding, as it implies that the participant's interpretation of the tracking task may be more important than the sonification technique used.

If this was also true for the training task it may account for some of the variability in learning outcomes, especially given that the nature of the sonification technique may influence the way people perceive the task. For example with the two-channel **AM** sonification the amplitude fluctuations in each ear tends to give the perception of a signal panning from left to right but this is not the case for the **FM** sonification thus people may approach the task differently depending on the nature of the sonification.

Thus at this stage it is unclear if there is no difference in tracking scores in experiment 3 between the two different sonifications, perhaps either because the tracking task does not work for two-channel sonification, or because both sonifications were both equally as good (or bad) as each other. However, the fact that there was very little difference between the two sonifications in the training task and the tracking scores are higher than in experiment 1, does suggest maybe the latter.

One possibility is that by making the two sonifications 'perceptually equivalent' in the third experiment, this may have 'normalised' their performance and this is why there is no differentiation between the sonifications, after all this was the point of making them perceptually equivalent.

For the **AM sonification** the maximum volume was set by the user but the maximum loudest the system could go to was 80 dB(A). For the first two experiments, all EEGs were normalised by dividing by 30 and linearly mapped for 0 to 1 which gave an output of 0 to 80 dB(A). But for experiment 3, the Alpha

EEG values from zero to the estimated maximum value of each participant, was exponentially mapped from 40 to 80 dB(A). This means that the AM sonification in the third experiment had a greater amplitude resolution, because the entire range of each person's EEG was fitted across the audible range, unlike some of the lower amplitude values in experiment 1.

For the **FM sonification** in experiment 1 and 2 the output frequency range was from 261.6 to 861.6 Hz (or from 523.2 to 1123.2 Hz in [experiment 1](#) only), making a frequency range of 600 Hz for both. Whereas in experiment 3, the frequency range was from 261.6 to 2637.02 Hz giving a range of 2375.39 Hz, which is nearly four times greater than the first experiments.

So it may not have just been adding a physical slider but the greater output range of the two sonifications in experiment 3 that could explain why there was better tracking accuracy scores than in the first experiment. Also because the two sonifications were made 'perceptually equivalent' they were able to convey the same amount of data and therefore achieved identical tracking accuracy scores between AM and FM.

An obvious question is whether an average correlation of just 0.3 between the EEG data and the tracking measure should be considered 'Good'. In the statistical literature it would be considered a 'weak' correlation ([see 6.7 Discussion](#)). But the more important question is whether this is sufficient to predict how well a sonification will do in real-time neurofeedback and can the slider distinguish between good from bad real-time sonifications.

Therefore the overall conclusion of the **tracking** task from the three experiments together must be that it works for single channel sonification, as there was a

difference between the two sonifications in the tracking and this was replicated in the training task, but it may not work for two-channel sonification as there was no difference in either the tracking or training. However this should be considered a provisional finding until the follow up experiment proposed in [7.5.2](#) below can be performed, where the sonifications from experiment 1 are tested with the physical slider from experiment 3. Furthermore, when many more different sonifications have been run through the experiment 3 protocol, the low correlation scores may not persist and it could be concluded it was the sonifications and not the tracking task that gave the low score in these experiments.

## **7.2.      Limitations**

The primary limitation in experiment 1 was the use of a mouse and slider on a computer screen in the tracking task, as this limited the speed that people were able to track the sonifications and this was rectified in the third experiment, with the use of a physical slider box.

In experiment 2 the primary limitation was the use of both sonification techniques in the same session, thereby restricting the amount of time people trained on each sonification and potentially introducing a carryover effect between the sonifications. Again this was rectified in experiment 3 by having two sessions with a different sonification in each making it possible to extend the training period to a more typical 20 minutes.

A limitation that will be remedied in the future is the lack of a test retest reliability assessment of the slider box and tracking task in the third experiment,

although the head-to-head comparison between the two sonifications does mitigate its absence.

The fact that there was no change in the EEG parameters in experiment 3 could be evidence that the group size was too small, despite recruiting the required number of participants suggested by the sample size estimates. This raises the dilemma of whether it is better to add more participants to the current protocol to up the group size, or start a new experiment with different sonifications. Beyond this current research, in order to help address this question, it will be necessary to explore the data further to identify the impact of responders vs. non-responders, i.e. the fairly standard procedure in neurofeedback research of splitting the group by those who showed a change in the intended direction and those that didn't.

Possibly the biggest limitation overall was the lack of a 'sham' no feedback group in the training sessions. Although this limitation is prevalent in the neurofeedback literature, it is difficult to be definitive about any pre to post changes in physiology without taking into account a host of non-specific confounding variables, such as interaction with the experimenter, sense of mastery or otherwise achieved doing the task, or simply sitting still for 20 minutes. Adding a sham feedback group is always a dilemma in neurofeedback studies because it adds so much time and cost to the experiment and it is considered unethical when working with a patient group that already has a known intervention. Also there is an argument that suggests that in a cross over design, if the sham feedback trials are administered before the real feedback trials, participants will learn that they cannot modify their

physiology and develop a sense of “learnt helplessness” (Seligman, 1972) that will carry over into the real feedback trials.

Of course a major limitation that will be remedied in follow-up experiments is that there was only the AM and FM sonification techniques used in the three experiments and on the other side there was only the tracking and training assessments. Obviously it would have been interesting to run all of the different sonification techniques through all of the different testing procedures identified in the literature review but these are the compromises that all research must make and the AM and FM sonification techniques represent a good baseline to build on.

### **7.3. Contribution to Knowledge**

The primary contribution to knowledge of this research is the development and validation of an assessment battery that could help to elucidate the relative merits of an EEG sonification to convey the rich and complex temporal dynamics of the real-time EEG data. The combination of tracking and training trials allows a qualitative and quantitative measurement of the real-time sonification that can assist in the rapid development of new sonifications that could be appropriate for neurofeedback.

Although the idea of comparing two different sonification techniques on the same task may seem obvious and the concept of tracking a sound in real-time with a slider as an assessment tool has been around since the 1990s. It does need to be pointed out that very few of the EEG sonification studies found in



the literature review have used these assessments or even conducted a quantitative evaluation or comparative ranking of a sonification's ability to convey the real-time EEG data.

Because the tracking task can assess multiple sonifications in a single session, this reduces the number of sessions and subjects needed for an experiment and does not require such rigorous ethical approval. This allows the rapid prototyping of multiple sonification techniques prior to any arduous neurofeedback study.

This research has specifically chosen open source and free resources where possible. The NASA-TLX, Mood and AttrakDiff questionnaires are freely available and the NASA-TLX has a free On-line version as well as free Apple and Android apps. The tracking task and questionnaire presentation was made in an open source software called **PsychoPy** (Peirce, 2007), The sonifications for the first two experiments were made in an open source sound synthesis software called **Pure Data** (Puckette, 2002). The commissioned custom-made sonification software used in experiment 3 is currently not open source. Furthermore the anonymised EEG and questionnaire data, as well as the assessment software, the Pure Data 'patches' to make the sonifications, plans and components lists for the slider hardware, as well as the 'r' scripts and SPSS syntax for the statistical analysis and findings will be deposited on a public database to allow for replication and in the hope of stimulating more research into real-time EEG sonification for neurofeedback.

Additionally the slider and NASA-TLX combination could be a useful assessment tool for a wide range of 'Non-EEG' real-time sonification applications and

provide a much needed quantitative assessment, especially for lower temporal resolution data streams.

Thus this research proposed and tested a method specifically tailored for the assessment of real-time EEG sonification for neurofeedback.

The dissertation has presented a prototype version of a quantitative assessment tool for comparing the temporal dynamics of real-time EEG sonifications. This approach has the potential to allow the quantitative comparative assessment of multiple sonification techniques in a much more rapid and agile fashion than conventional approaches.

#### **7.4. Further work**

This section will explore some of the potential future studies that could replicate and build on this current research.

##### **7.4.1. Group size**

A simple and useful follow-on experiment would be to run the experiment 3 protocol with more participants. For example, increasing the group size up to at least 30 participants would achieve a statistical power of 0.998 (as seen in [section 6.3.2](#)). If sufficient participants could be recruited, it may be possible to split the group by responders vs. non-responders and still have sufficient statistical power within the responders group.

#### 7.4.2. Slider box

A second simple follow-on experiment would be to repeat the first experiment of single-channel sonification tracking with the new slider box used in experiment 3. This would allow an assessment of the physical box's impact on tracking accuracy.

#### 7.4.3. Test-Retest Reliability

One useful step to strengthen the validity of the new tracking test outlined above would be to run a series of test-retest reliability experiments. This would require the participants to do the tracking task multiple times in order to establish the correlation between multiple replications of the same trial in order to estimate the measurement error of the tracking task.

It may be efficient to replicate several different sonifications in the same session and it would be interesting to start with the four sonification techniques used in the current three experiments, i.e. the one channel AM and FM sonifications from experiment 1 & 2, and two-channel AM and FM sonifications from experiment 3. (Such an experiment would negate the need to run the slider box experiment suggested above).

But it would also be valuable to see how the 'perceptual equalisation' modifications made in experiment 3 affected the tracking accuracy scores. So four new sonifications could be made, i.e. single channel AM and FM sonifications that are 'perceptually equivalent', as in experiment 3, along with twin-channel AM and FM sonifications without the 'perceptual equivalence' mapping.

If all 8 sonifications were used in one minute tracking trials and the two-channel sonifications were run twice with the two different instructions (a.k.a. orientations) as used in experiment 3, this would make 12 trials. Despite the seeming proliferation of conditions, if this was repeated twice, this would still require no more than 24 one minute trials, which should take less than 40 minutes to run for each session.

As well as establishing the test-retest reliability of the tracking task, such an experiment could clarify the impact of making the sonifications 'perceptually equivalent', as well as comparing the One vs. two channel sonifications.

It would also be interesting to run the same protocol with some new sonifications as well as seeing if people could track the 'activity' of three or more channels of sound.

#### **7.4.4. One and two channel frontal alpha asymmetry sonifications**

An interesting next experiment would be to run the experiment 3 protocol on the two channel frontal alpha symmetry EEG but compute the asymmetry prior to sonification, so there would only be one stream of sound. If the tracking accuracy scores were much higher than in the current experiment 3, this would suggest participants were less able to perceive the frontal alpha symmetry measure from a two-channel sonification, but if the neurofeedback training outcomes were worse, this would support the concept of multiple streams of sonification.

#### **7.4.5. More sonifications**

21 different real-time EEG sonification techniques were identified in the literature review, of which only 6 have been used in a neurofeedback study: AM, FM, Filtered Sonifications, Parameter mapping, Event-based/Threshold and Tristimulus synthesizer. Thus it would be interesting to run all of these sonification techniques through the experiment 3 protocol, to see if any stood out as potentially being more appropriate for neurofeedback.

### **Temporal Resolution:**

One of the prime motivations behind this research was to explore how well the rapid temporal complexity of the EEG could be conveyed with sound. Therefore it would be interesting to test how different levels of temporal averaging or windowing of the sonification would impact accuracies on the different assessment tools.

For example as the window length is increased and the amount of temporal averaging goes up, it is likely the tracking accuracy scores will increase, because in effect the signal is slowed down and the delays introduced by the motor movement of the slider will become less significant. However after a certain length of windowing, the accuracy on the 2AFC, 'Temporal Onset Detection' or neurofeedback task is likely to decrease as too much information is being lost from the original EEG signal because of the averaging.

Thus with an experiment with a sonification with multiple different temporal window lengths, of for example: 100, 200, 500, 1000 and 3000 ms and different window overlaps, it may be possible to elucidate the optimal level of temporal

averaging to balance between the faithfulness to the original EEG signal on one hand and the intelligibility for the user of the signal on the other.

### Amplitude Resolution and Sonification Output Range:

But of course there are two aspects to the resolution of the measurement and display of the temporal dynamics of the EEG: the temporal and the amplitude resolution. The temporal resolution is how many data points in time i.e. samples per second and amplitude resolution is how many samples in amplitude i.e. bit depth. In terms of the accuracy of the amplitude measurement, or input sensitivity, modern EEG amplifiers like the Mitsar used in the third experiment now have a bit depth or amplitude resolution of 24 bit, (i.e. **16,777,215** data values).

However, in terms of 'displaying' the EEG data in neurofeedback, the situation is not so clear. For example in neurofeedback training it is common to use a threshold criterion for the reward, where only when the EEG activity of interest crosses a set threshold will a reward be given and something on the screen will move or change. This could be seen as having a bit depth of 1, i.e. on or off. Yet most neurofeedback systems will also display continuous activity across the full range of the EEG parameter, for example as a bar graph. However the resolution of the displays is not reported. Therefore it is difficult to know a priori what an appropriate range would be, which could be somewhere between a bit depth of 1 equivalent to threshold criterion and 24 bit which would be the maximum resolution of the EEG measurement.

The three experiments in this research have started to try and unpick how the amplitude and frequency output range can impact the accuracy of the AM and FM sonifications. The sonifications in experiment 3 had a greater output amplitude and frequency range for a given EEG input, with an attempt to make the output of the sonification equate to 40 JNDs across the range of EEG input. Experiment 3 did get higher tracking accuracy scores but did not show better neurofeedback training outcomes, so there is still much more to do in this domain.

So a simple experiment would be to make several of the same type of sonification techniques with different output ranges, for example the FM sonifications with different frequency output ranges. The tracking task should be adequate for assessing the different frequency resolutions, as there would be no temporal difference between the sonifications.

### **Multiple Auditory Streams:**

Another dimension of interest that these current experiments started to explore was the use of multiple auditory streams of the EEG data. These experiments were only able to explore one and two channel sonifications, but as with the temporal averaging there may be an optimum level. As the number of channels is increased, the amount of information that can be perceived increases until a certain point when saturation is reached and intelligibility may even decline with more channels.

### **Combine multiple auditory streams & temporal averaging:**

One interesting possibility would be to combine the two points above and use the fanning sonification technique (Barrass et al., 2006) where the same data is simultaneously presented in multiple different ways. So for example it could be possible to play five different audio streams that are spatially distributed over five different temporal window lengths. Then the question would be, do participants perceive the sonification as five separate audio streams, where they can choose which audio stream has the most appropriate window length to perceive the data, or do they perceive it as one overall gestalt with both trend and high-frequency information. This could also be possible with multiple voices or instruments for the five different audio streams (See: Spectral mapping: in A2.4 Sonification Techniques).

### **Aesthetic Quality:**

Only slightly touched upon in this research but nonetheless an important aspect is the aesthetic quality of the sonifications. It is quite probable that if the sonification had an aesthetically pleasing sound, there would not have been the two dropouts in experiment 3, but it is an empirical question whether this would increase tracking accuracy scores or data perception. And of course there is a great danger of compromising the fidelity of data transformation in the quest for beauty.

A simple way to improve the aesthetic quality of the AM sonification technique would be to replicate the van Boxtel sonification (See section: 3.7.9. van Boxtel, 2012), or Wand (See section 3.7.11. Wang, 2013) but with a fixed selection of relaxing music.



Therefore the first three aspects of the sonification to explore will be the temporal averaging, multiple auditory channels and the aesthetic quality of the sonifications.

#### **7.4.6. Multiple assessment battery**

A potentially useful contribution to the field of EEG sonification would be to measure a number of different sonification techniques on a variety of assessment tools, such as the 'two-alternative forced choice' method (See [section 3.6.2](#)), the 'Temporal Onset Detection' task (See [section 3.6.3](#)) as well as the tracking task. The NASA-TLX (See 4.2.6. Measure 3: Qualitative - NASA-TLX) did prove useful in this research, however the AttrakDiff (See 5.3.5.3. Measure 3: AttrakDiff and 3.6.1. Aesthetic Assessment) did not show much utility although this may have been the fault of the sonifications rather than the questionnaire. However a more comprehensive assessment of the aesthetic quality of the sonification could be justified.

The primary motivation for developing the assessment protocol was to try and quantify how well a real-time sonification can convert and convey the EEG data into sound. Therefore one question could be to explore how much information is in the EEG data and how much of that information was then converted into sound. Several methods to quantify this were explored and some preliminary work was carried out looking at Approximate Entropy. Approximate Entropy is a statistical measure of regularity and the unpredictability of a dataset over time. i.e. if you know the current data point, how well can you predict the next. Approximate Entropy has shown some utility

with EEG in measuring the complexity of EEG in different sleep states and under anaesthesia (Bruhn et al., 2000). But in the end it was felt that the topic of entropy was beyond the scope of this current research and that having a solely statistical measure of the data transformation without looking at how well the sound of the EEG had been preceded, would not be as convincing and could not provide the 'ground truth' that is needed, thus the tracking task was designed.

However, just as with the tracking task, if a measure like Entropy could make a comparative estimate between two or more sonifications, of how much information was in the EEG and the sound, then the relative ability of a sonification to convert the real-time EEG data could be assessed. This would be part of a wider effort to find metrics that were able to detect the rapid and complex temporal Dynamics of the EEG.

#### **7.4.7. Full neurofeedback experiment**

If the experiment 3 replication above identified some promising sonifications, the next obvious step would be to run a full EEG sonification neurofeedback experiment with 30 participants with a minimum of 10 sessions of neurofeedback each, for least 20 minutes per session, with pre and post 'full cap' EEG and psychometric measures. This could take around a year of work for one researcher, but could provide suitable evidence of the utility of sonification for neurofeedback. Subsequent experiments could then replicate this new neurofeedback experiment with different patient populations, such as people with depression or anxiety.

This does highlight the need for a rapid assessment protocol that can pre-screen many sonification techniques prior to such a labour-intensive study and shows some of the limitations of a PhD study.

#### 7.4.8. Next Steps

Although the ultimate goal will be to validate any sonification with a full neurofeedback study, this is considered premature until some of the validation studies mentioned above can be conducted.

Thus the next step will be to combine several of the elements mentioned above into one experiment, by designing an experimental protocol that combines:

- **Multiple 'within subject' test-retest reliability trials**
- **With multiple assessment tools (including the new slider box)**
- **On multiple sonification techniques**
- **With at least 30 participants in each trial**

The first aspects to look at would be temporal averaging of the sonification. Thus two different window lengths of a single channel FM sonification will be tested using the same protocol as in experiment 3, but with the addition of a new measure of the aesthetic quality of the sonification. This would require 4 sessions for each participant instead of the two sessions in experiment 3 to look at the test retest reliability of the tracking task.

With the series of these experiments, this design could potentially establish which assessment tool is more appropriate for the evaluation of real-time EEG

sonifications, as well as identifying potential candidate sonifications to take forward to the full real-time neurofeedback experiment above.

## **7.5. Conclusion**

The aim of this research was to develop real-time EEG sonifications for use in neurofeedback and develop methods for assessing the sonifications ability to convey the EEG data.

The findings from this research show that people are able to physically track the continuous EEG signal with a slider but explicit test-retest reliability experiments are needed to establish if the tracking task can provide a quantitative assessment of the relative ability of sonifications to convey the complex temporal dynamics of EEG.

Furthermore the results showed that people did change self-rated mood in the predicted direction with the use of real-time FM sonification of their own frontal Alpha brain waves. However without a sham or placebo control group it is difficult to be definitive about the course. Moreover, to some extent the tracking task can predict training outcomes.

This assessment protocol has the potential to be applied to many different sonification techniques with a range of different temporal resolutions or other acoustic properties, in order to establish the optimal settings for the presentation of real-time EEG sonifications for neurofeedback.

If these findings can be replicated and more sonifications validated, the use of real-time EEG sonifications has the potential to become a useful therapeutic

training tool in the medical, educational and peak performance domains and potentially help millions of people to modify their own physiology.

## Chapter 8: References

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## Chapter 9: Appendices

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## A2.1 EEG Sonification Conferences:

Conferences: (N. 42)	Acronym	N.
Amber Art & Technology Conference	(Amber)	1
American Epilepsy Society	(AES)	1
Asia-Pacific Signal and Information Processing Association	(APSIPA)	1
Audio Engineering Society Convention	(ASE)	1
Australasian conference on Computer-Human Interaction	(OZCHI)	1
Berlin BCI Workshop - Advances in Neurotechnology	(BBCI)	1
CHI Conference Workshop on Sonic Interaction Design	(CHI)	2
Computer Music Modelling and Retrieval Conference	(CMMR)	1
Computer-human interaction special interest group	(CHISIG)	1
Conference on Cognitive Neurodynamics	(ICCN)	1
Electronics in Marine	(ELMAR)	1
Engineering in Medicine and Biology Society	(EMBS)	5
eINTERFACE	eINTERFACE	2
Gerontechnology		1
Information Comm. of Technology, Electronics and Microelectronics	(MIPRO)	1
Information Visualisation	(IV)	1
Institution of Engineering and Technology, Seminar on Assisted Living	(IET)	1
Int'l. Community for Auditory Display	(ICAD)	19
Int'l. Computer Music Conference	(ICMC)	4
Int'l. Conference Acoustics, Speech and Signal Processing	(ICASSP)	2
Int'l. Conference on Cyberworlds	(CW)	1
Int'l. Conf. on Disability, Virtual Reality & Associated Technologies	(ICDVRAT)	2
Int'l. Conference on Enactive Interfaces	(ENACTIVE)	1
Int'l. Conference on Information and Emerging Technologies	(ICIET)	1
Int'l. Conf. on Information Sciences, Signal Processing & their App.	(ISSPA)	1
Int'l. Conf. Knowl-Based & Intelligent Information & Engineering Sys	(KES)	1
Int'l. Conference on Neural Computation Theory and Applications	(NCTA )	1
Int'l. Conference on Neural Information Processing	(ICONIP)	2
Int'l. Conference on New Interfaces for Musical Expression	(NIME)	7
Int'l. Conference on Pervasive Computing and Applications	(ICPCA)	1
Int'l. Conference on Physiological Computer Systems	(PhyCS)	1
Int'l. Conference Speech and Computer	(SPECOM)	1
Int'l. Federation for Medical and Biological Engineering	(IFMBE)	1
Int'l. Symp. on App. Sciences in Bio-Medical and Com. Technolog.	(ISABEL)	1
Int'l. Symp. on Noninvasive Functional Source Imaging of Brain & Heart	(NFSI)	1
Int'l. Workshop on Biomedical Circuits & Systems IEEE	(BIOCAS)	1
Int'l. Workshop on Interactive Sonification	(ISon)	3
Irish Signals and Systems Conference	(ISSC)	1
Proceedings of Music, Mind and Invention Workshop	(MMI)	1
Proceedings of Sound and Music Computing	(SMC)	2
World Congress on Medical Physics and Biomedical Engineering		1
Pan American Health Care Exchanges	(PAHCE)	1

## A2.2 EEG Sonification Journals and 5-Year Impact Factor:

Journals: (N. 48)	Impact	N.
Advances in Human-Computer Interaction	1.9	1
Advances in mind-body medicine	1.62	1
Alcoholism: Clinical and Experimental Research	2.829	1
American journal of neurodegenerative disease	3.06	1
Annals of the New York Academy of Sciences	4.039	1
Applied Psychophysiology and Biofeedback	1.56	1
Biomedizinische Technik	0.745	1
BMC Neuroscience	1.314	1
Brain and Behavior	2.287	2
Brain, A Journal of Neurology	9.457	1
Clinical Neurophysiology	3.76	2
Computational Intelligence and Neuroscience	0.47	1
Computer Music Journal	0.756	1
Current opinion in anaesthesiology	1.916	1
Decision Support Systems	3.271	1
Engineering in Medicine and Biology Magazine	2.057	1
Epilepsy & Behavior	2.098	1
Experimental brain research	2.221	1
Finnish Journal of eHealth and eWelfare	0.57	1
Frontiers in Human Neuroscience	3.634	1
Frontiers in Neuroscience	3.398	1
Future Generation Computer Systems	1.594	1
Information Technology in Biomedicine	1.676	1
Intelligent data analysis	0.448	1
Interacting with Computers	1.64	1
International Journal of Arts and Technology	1.582	1
International Journal of Human Computer Studies	2.097	2
International Journal of Multimedia and Ubiquitous Engineering	0.6	1
International Journal of Neuroscience	1.537	1
International Journal of Psychophysiology	2.817	1
Journal of Clinical Psychology	2.024	1
Journal of Neuroscience Methods	2.256	1
Journal of Neurotherapy	na	1
Journal of the Japanese Society for Sonic Arts	na	1
Journal of Zhejiang University SCIENCE C		1
Leonardo Music Journal	0.14	3
Medical & Biological Engineering & Computing	1.88	1
Medical Hypotheses	1.15	1
Multimedia	1.754	1
Music and Medicine	na	1
Neuron	16.092	1
Neuropsychobiology	1.224	1
Neurorehabilitation and Neural Repair	4.278	1
Neuroscience bulletin	1.365	1
PLOS ONE	4.411	3
Psychophysiology	3.074	3
Science	35.26	1
Sleep Medicine	3.564	1

### A2.3 Sonification Neurofeedback Journals and 5-Year Impact Factor:

Name	Journal	Impact
<b>Nowlis, 1970</b>	Psychophysiology	3.074
<b>Schwartz,, 1976</b>	Psychophysiology	3.074
<b>Hardt, 1978</b>	Science	35.26
<b>Allen 2001</b>	Psychophysiology	3.074
<b>Fell, 2002</b>	International Journal of Neuroscience	1.537
<b>Le Groux, 2009</b>	International Conference on Auditory Display	-
<b>Trevisan, 2011</b>	Proc. IET Seminar on Assisted Living	-
<b>Hinterberger 2011</b>	Advances in Human-Computer Interaction	1.90
<b>Choi 2011</b>	Neuropsychobiology	1.224
<b>van Boxtel, 2012</b>	International Journal of Psychophysiology	2.817
<b>Hardt, 2012</b>	Advances in mind-body medicine	1.62
<b>Wang, 2013</b>	BMC Neuroscience	1.314
<b>Ramirez 2015</b>	Frontiers in Neuroscience	3.398
<b>Hinterberger 2016</b>	Applied Psychophysiology and Biofeedback	1.56

## A2.4 Sonification Techniques:

### Audification:

Audification is the oldest (Adrian and Matthews, 1934) method of EEG sonification and is perhaps the simplest. As de Campo et al., (De Campo et al., 2007) points out, *"straightforward audification is the obvious choice, as it allows for keeping the rich detail of the signals entirely intact. With sampling rates around 250 Hz, a typical speedup factor is 60 x faster than real-time, which transposes our centre band (alpha, 8-16Hz) to 480-960 Hz, well in the middle of the audible range. For more time resolution, one can go down to 10 x, or for more speedup, up to 360 x"*. However, Baier et al., (Baier and Hermann, 2004) say audification *"often fails to let the most interesting attributes stand out in the auditory display"*.

### Amplitude Modulation (AM):

*"A fundamental sonification idea is to simply use the amplitude of variable X to modulate the intensity of a given stationary sound. Thus spikes describe the amplitude envelope"*. (Baier, Hermann, Lara, et al., 2005)

### Frequency Modulation (FM):

Wu et al, (Wu et al., 2009) *"established a sonification rule between the amplitude of an EEG waveform and the Pitch of a musical note (the logarithm of frequency)"*, it is suggested this is better than mapping the amplitude of the EEG to the amplitude of notes as for one reason the amplitude will need to be adjusted for comfortable listening and secondly, human hearing is better at discriminating fine pitch changes than amplitude changes.

### Filtered Sonifications:

Again this is a very simple sonification where the frequency response of a piece of music is modulated by a simple high-pass filter driven by the amplitude of the EEG, van Boxtel, (van Boxtel et al., 2012) says it "greatly affected music quality, making the music sound very distant and thin"

### Spectral mapping:

Hermann et al, (Hermann et al., 2002) say of Spectral mapping *"the activity in a specific spectral band can be monitored. Assume, we are interested in the alpha-band from 8 Hz to 13 Hz. As the window width is 1 sec we have a frequency resolution of 1 Hz and thus 6 frequency cells are within the selected range. Thus 6 time-variant oscillators are created which monitor signal energy as loudness. Suited time compressions are about 50, allowing to monitor 50 seconds of experimental data in 1 sec. If more than one channel is of interest, the sonifications of chosen channels can be superimposed. To compare different regions, each channel can be assigned to the left or right stereo channel"*. And also *"Spectral Mapping Sonification allows frequency-selective browsing of EEG data"*.

### Distance matrix:

Hermann et al. (Hermann et al., 2002) describes distance matrix sonification as *"allows to detect nonlinear long range correlations at high time resolution"* (sic) He goes on to point out that 'distance matrix sonification' highlights *"the synchronization of different brain areas as a function of time"* and he gives this equation.

$$D_{ij}[m] = \|\tilde{\mathbf{s}}_i[m] - \tilde{\mathbf{s}}_j[m]\| \quad (4)$$

Differential:

A thread sonification presented by Hermann et al. 2002 is 'differential sonification' that "allows the comparison of data recorded for one subject under different conditions in order to accelerate the detection of interesting channels and frequency bands along which the conditions may cause systematic differences". And he gives this equation, (Hermann et al., 2002)

$$\sigma_{\alpha,\beta,k}^i = \sqrt{K((N_{i,\alpha} - 1)(\sigma_{\alpha,k}^i)^2 + (N_{i,\beta} - 1)(\sigma_{\beta,k}^i)^2)}$$

$$K = \frac{1}{\nu} \left( \frac{1}{N_{i,\alpha}} + \frac{1}{N_{i,\beta}} \right)$$

#### Neurogranular sample:

"The Neurogranular sampler works by triggering grains of sound (typically in a range of duration of 10 milliseconds to 50ms) taken from a recorded sample when any one of an isolated network of artificial cortical neurons 'fires'. The resulting sound therefore consists of short bursts of the original sample triggered by the cortical neurons". (Grant et al., 2009)

#### Timbre mapping:

In the same paper Baier et al. (Baier, Hermann, Lara, et al., 2005) describe 'Timbre Mapping' as an *"additive synthesis with energy distributed on N harmonics for the events and - as a first example - use the intra-spike distance (time until the other time series spikes) to determine N for every spike. The larger*

*this time, the more brilliant the sound. Thus rhythmical structuring also induces timbral structures".*

### **Parameter mapping:**

This "sonification belongs to the class of indirect continuous parameter mapping sonification. The mapping is indirect in the sense that not data, but data-driven features are used to control synthesis parameters; it is continuous, since here a continuous sound signal is computed so that only a single speaker is perceived", (Hermann et al., 2006).

In his paper "uses of excitatory/articulatory speech model and a particularly selected parameter mapping to obtain auditory gestalts (or auditory objects) that corresponds to features in the multivariate signals. The sonification is adaptable to patient-specific data patterns, so that only characteristic deviations from background behaviour (pathologic features) are involved in the sonification rendering" (sic).

### **Event-Based Sonification:**

Event-based sonification uses pre-defined data features to trigger sounds, this "suppresses irregular background and highlights normal and pathologic rhythmic activity". It "can easily be implemented for real-time applications" and can be "extended to facilitate the detection of cross-correlations, e.g. phase relationships between rhythms from different sources" (Baier et al., 2007; Baier, Hermann and Müller, 2005).

### **Auditory icons**

Auditory icons are the auditory equivalent of the visual icons, "Auditory icons mimic everyday non-speech sounds that we might be familiar with from our everyday experience of the real world" (Brazil and Fernström, 2011).

### **Earcons**

Earcons are abstract or arbitrary symbolic representations and "Earcons do not share the relationship with events or objects in the real world" (Brazil and Fernström, 2011).

### **Flanging:**

"Flanging is created by mixing a signal with a slightly delayed copy of itself, where the length of the delay, less than 10 ms, is constantly changing. Instead of creating an echo, the delay has a filtering effect on the signal, and this effect creates a series of notches in the frequency response. This varying delay in the flanger creates some pitch modulation (warbling pitch)" (Arslan et al., 2005).

### **Granulation:**

The "Granulation techniques split an original sound into very small acoustic events called grains of 50 ms. duration or less, and reproduces them in high densities ranging from several hundred to several thousand grains per second. A lot of transformations (time stretching, pitch shifting, backward reading) on the original sound are made possible with this technique" (Arslan et al., 2005).

### **Extrema detection:**



“Characteristic rhythms of the EEG ... are sonified by triggering the touches of a note at the maxima of a wave... As a maxima can only be detected after it occurs (one processing step= $1/128$  s afterwards) an additional latency of about 8 ms. arises. In addition, the potential differences between subsequent extrema (maxima minus previous minima or minima minus previous maxima) are calculated. The three output signals of this filter carry the potential differences together with the times where the extrema were detected, otherwise they are zero”. (Hinterberger et al., 2004)

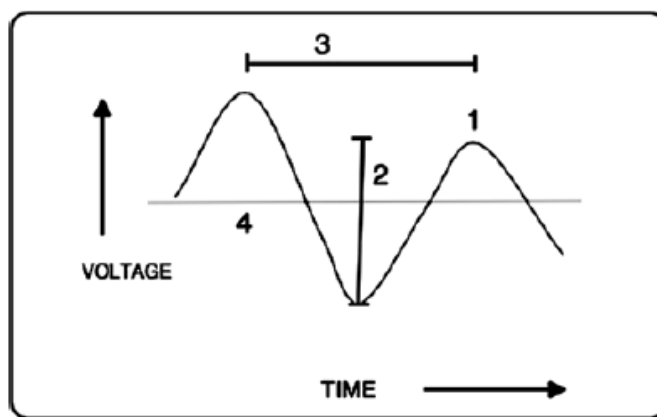


Fig. 1. Parameters for sonification. 1: voltage maximum; 2: voltage difference between present maximum and previous minimum; 3: time difference between present and previous maximum; 4: threshold voltage.

### Generative rules music engine:

“The analysis module performs EEG analyses in real-time to generate two streams of control parameters: (i) information about the most prominent EEG frequency band, extracted using power spectrum analysis; (ii) information about complexity of the signal, extracted using Hjorth analysis. The first stream is used by the music engine, to generate the music (applying a set of generative music rules, each of which produce a musical bar, or measure)... The second stream controls the tempo of the music. Every time the music engine has to

produce a bar, it checks the EEG power spectrum and activates rules associated with the prominent EEG rhythm in the signal. The system is initialised with a reference tempo, which is constantly modulated by the signal complexity analysis". (Brooks et al., 2007)

#### **Kernel regression mapping:**

"Kernel regression allows to map data spaces to high dimensional parameter spaces such that specific locations in data space with pre-determined extent are represented by selected acoustic parameter vectors. Thereby, specifically chosen correlated settings of parameters may be selected to create perceptual fingerprints, such as a particular timbre or vowel". Also, "Kernel regression is a standard approach to compute smooth interpolations between given output vectors". (Hermann et al., 2008)

#### **Tristimulus synthesizer:**

In a paper by Le Groux et al. (Le-Groux and Verschure, 2009), he is "*Inspired from the tristimulus theory of colour perception*" this sonification technique used "*real-timemodulation of precomposed musical cells*", and with a misunderstanding of the word tristimulus, Le Groux claims "The tristimulus synthesizer allows control over tristimulus parameters, ADSR envelope, noisiness, loudness, inharmonicity and vibrato".

It is difficult to tell from the limited description but this could be a form of 'Event-Based Sonification'.

#### **Overtone mapping:**

In a paper by Terasawa et al. (Terasawa et al., 2012) they describe an example of Overtone mapping *"The sonification of the 16-channel excerpt data was done using the following procedure.*

1. The fundamental frequency was set to 180 Hz.
2. Harmonics of 16 sinusoids (up to the 16th harmonics) were created.
3. Each harmonic was amplitude-modulated by each channel: the 1st harmonic is modulated with channel 1, the 2nd with channel 2, and so on.
4. All of the harmonics were summed, creating a single audio signal.
5. The audio signal was linearly scaled with its maximum value, so that the scaled signal could fit within the .wav file dynamic range"

### **Spatial location:**

Spatial location uses the spatial location of the sound output in audio space to convey extra information about the content of the data set. Baier et al. (Baier et al., 2007) gives an example where the spatial coordinates of the electrodes from a multivariate EEG recording are mapped to the azimuth angle in a multi-speaker system.

### **Funnelling & Fanning:**

*Funnelling* is where multiple data sources are combined in a single sound generator and *fanning* is where a single data source controls aspects of multiple sound generators (Barrass 2006).

### A3.1 Recruitment Sheet

## Real-Time Alpha EEG Data Sonification Study 3 2016

Principal Investigator: **Tony Steffert** (Supervisors: **Simon Holland** and **Paul Mulholland**)

**Study question:** Can real-time sonification of EEG help people learn to modify their frontal Alpha asymmetry brain waves activity and what impact will different sonifications of data have on learning outcomes.

This study will entail two sessions that should take around 75 minutes each, a week or more apart at around the same time of day. We will be seated alone at a desk in a quiet room in front of a laptop with headphones. First you will be asked to listen to a 1 minute sound file twice and try and track its activity with a slider and you will then be asked how easy or difficult you found the tracking. Then you will be asked to rate "how you feel right now" on 9 scales and you will be asked the same questions at the end of the study.

Then I will record the electricity from your brain (call Electroencephalography or EEG) and you will get to see your brain waves. The EEG will be turned in to sound so you can hear your own brain activity. Then you will be asked to try to change the sound with your mind. There will be 8 trials of 4 minutes with a short break in-between each.

You can choose from five locations between now and November 2016:

- The Open University Camden campus at 1-11 Hawley Crescent NW1 8NP
- Jennie Lee building at The Open University in Milton Keynes
- Learning Recovery clinic in Cambridge, 182 Kings Hedges Rd, CB4 2PB
- The London Neurology and Pain Clinic, 100 Harley St, London
- Birkbeck, University of London (TBA)

If you would like to volunteer for this study you must be over 18 years old

**Please do not volunteer for this study if you have a history of any of the following:**

- Any problem with your hearing as this is a listening study
- History of convulsive disorders, Epilepsy or other seizures
- Major Head injury with loss of consciousness
- Recent psychoactive drug use, either prescription or recreational for two days prior to study. (Please do not stop any medication to take part in this study)

Please email: **tony.steffert@open.ac.uk** if you would like to take part in this study.

All data collected will be anonymised and encrypted and your contact data will be kept confidential. In accordance with the Open Data Principles for the Research Councils UK, that says that "Publically funded data should be open". The anonymised EEG, tracking and questionnaire data will be permanently deposited on a publicly open database to encourage further research in to EEG sonification.

You will be free to withdraw from the study at any time without explanation or prejudice and have any unprocessed data withdrawn.

If you have any questions please email me, **Tony Steffert** [tony.steffert@open.ac.uk](mailto:tony.steffert@open.ac.uk) or my supervisors **Simon Holland** ([simon.holland@open.ac.uk](mailto:simon.holland@open.ac.uk)) and **Paul Mulholland** ([paul.mulholland@open.ac.uk](mailto:paul.mulholland@open.ac.uk))  
Thank you

## A3.2 Information Sheets

Information sheet: Please keep for your reference.

### Real-Time Alpha EEG Data Sonification Study 1B 2015

Principal Investigator: Tony Steffert (Supervisors: Simon Holland and Paul Mulholland)

**Study question:** Can real-time sonification of EEG help people learn to modify their simultaneous frontal Alpha brain waves activity and what impact will the sonification have on learning outcomes.

This study should take around 40 minutes. All data collected will be anonymised and encrypted and all data analysis and publications will be based on the anonymised data and your data will be kept confidential.

You are free to withdraw from the study at any time without explanation or prejudice and to withdraw any unprocessed data.

First you will be asked to rate “how you feel right **now**” on 9 scales and you will be asked the same questions at the end of the study.

Then your brain activity will be measured from two locations on your head. This will require a headset with 7 leads being placed on your head and behind your ears. The electrodes only measure the very small currents from your brain and it will not hurt.

Then you will be asked to listen to the sound of your brain waves and try to change the sound with your mind. There will be 3 trials of 3 minutes with one sonification with a short break in-between each. Then you will be asked to rate your mood again and on two different questionnaires what you thought of the sonification. This will then be repeated with a second sonification.

If you have any questions please ask now before signing the consent form. You could email me or my supervisor Simon Holland ([simon.holland@open.ac.uk](mailto:simon.holland@open.ac.uk)) and Paul Mulholland ([paul.mulholland@open.ac.uk](mailto:paul.mulholland@open.ac.uk))

**Thank you for participating.**

**Tony Steffert**

Computing and Communications Department  
The Open University  
[tony.steffert@open.ac.uk](mailto:tony.steffert@open.ac.uk)  
Mob: 07966 484 289

**Please keep for your reference.**



## **Real-Time Alpha EEG Data Sonification Study 3 2016**

Principal Investigator: Tony Steffert (Supervisors: Simon Holland and Paul Mulholland)

**Please do not volunteer for this study if you have a history of any of the following:**

- Any problem with your hearing as this is a listening study
- History of convulsive disorders, Epilepsy or other seizures
- Major Head injury with loss of consciousness
- Recent psychoactive drug use, either prescription or recreational for two days prior to study. (Please do not stop any medication to take part in this study)
- Also you must be over 18 years old

**Study question:** Can real-time sonification of EEG help people learn to modify their simultaneous frontal Alpha asymmetry brain wave activity and what impact will different sonification methods have on learning outcomes.

This study will entail two sessions of around 75 minutes each, a week or more apart at around the same time of day. All data collected will be anonymised and encrypted and all data analysis and publications will be based on the anonymised data and your data will be kept confidential. In accordance with the Open Data Principles for the Research Councils UK, that says that "Publically funded data should be open". The anonymised EEG, tracking and questionnaire data will be permanently deposited on a publicly open database to encourage further research in to EEG sonification.

You will be free to withdraw from the study at any time without explanation or prejudice and to withdraw any unprocessed data prior to publication, (please contact Tony Steffert by the 30/11/2016 to withdraw any data).

**The study session:**

We will be seated alone at a desk in a quiet room in front of a laptop with headphones. First you will be asked to listen to a 1 minute sound file twice and try and track its activity with a slider and you will then be asked how easy or difficult you found the tracking. Then you will be asked to rate "how you feel right now" on 9 scales and you will be asked the same questions at the end of the study.

Then your brain activity will be measured from two locations on your head. This will require 4 leads being placed on your head. A cap will be put on your head and the leads on the scalp will use a sticky conductive paste that will just wash off with a wet wipe. The electrodes only measure the very small currents from your brain and do NOT put anything in, measuring the EEG will not hurt and it is completely safe. But if you have any skin allergies to adhesives please let me know. I have recorded EEG from hundreds of people over the last 15 years and never had a problem.

Then you will be asked to listen to the sound of your brain waves and try to change the sound with your mind. You will hear two different sonifications in a random order and there will be 8 trials of 4 minutes each, with a short break in-between. One of the trials will not have any sound.

If you have any questions please ask before signing the consent form. If you would like a copy of the summary research findings please ask or email Tony Steffert at [tony.steffert@open.ac.uk](mailto:tony.steffert@open.ac.uk). You can also email my supervisors Simon Holland ([simon.holland@open.ac.uk](mailto:simon.holland@open.ac.uk)) and Paul Mulholland ([paul.mulholland@open.ac.uk](mailto:paul.mulholland@open.ac.uk))

Thank you

## Computing and Communications

Consent form for persons participating in a research project

### Real-Time EEG Data Sonification Study 1B 2015

Name of participant:

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Name of principal investigator(s): **Tony Steffert** (Supervisor's: Simon Holland & Paul Mulholland)

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1. I consent to participate in this project, the details of which have been explained to me, and I have been provided with a written statement in plain language to keep.
2. I understand that my participation will involve the recording and training of my EEG as well as the completion of Mood questionnaires and that the study should take around 40 minutes to complete. The anonymised EEG and psychometric data will be recorded and analyzed only for the purpose of the research and in no way will be used for risk screening or diagnosing purposes.
3. I acknowledge that:
  - (a) the possible effects of participating in this research have been explained to my satisfaction;
  - (b) I have been informed that I am free to withdraw from the project at any time without explanation or prejudice and to withdraw any unprocessed data I have provided;
  - (c) the project is for the purpose of research;
  - (d) I have been informed that the confidentiality of the information I provide will be safeguarded subject to any legal requirements;
  - (e) I have been informed that with my consent the data generated will be stored in an anonymised form on an encrypted storage device;
  - (f) if necessary any data from me will be referred to by a pseudonym in any publications arising from the research;
  - (g) I have been informed that a summary copy of the research findings will be forwarded to me, should I request this.

I wish to receive a copy of the summary project report on research findings ☐ **yes** ☐ **no**  
(please tick)

Participant signature:

Date:

---

Tony Steffert

Email:

Consent form for persons participating in a research project

**Real-Time EEG Data Sonification Study 3 2016**

Name of participant:

Name of principal investigator(s): **Tony Steffert** (Supervisor's: Simon Holland & Paul Mulholland)

1. I consent to participate in this project, the details of which have been explained to me, and I have been provided with a written statement in plain language to keep.  
(Please tick) ☐ **yes** ☐ **no**
2. I understand that my participation will involve the recording and training of my EEG as well as the completion of Mood questionnaires and that the study should take around 75 minutes to complete.  
The anonymised EEG and psychometric data will be recorded and analyzed only for the purpose of  
the research and in no way will be used for risk screening or diagnosing purposes.  
(Please tick) ☐ **yes** ☐ **no**
3. I acknowledge that:
  - (a) The possible effects of participating in this research have been explained to my satisfaction;
  - (b) I have been informed that I am free to withdraw from the project at any time without explanation or prejudice (please just inform me during the session if you wish to do so) or to withdraw any unprocessed data I have provided, (please contact me; Tony Steffert by the 31/09/2016 to withdraw any data);
  - (c) The project is for the purpose of research;
  - (d) I have been informed that the confidentiality of the information I provide will be safeguarded subject to any legal requirements;
  - (e) I have been informed that with my consent the data generated will be stored in an anonymised form on an encrypted storage device and any publications will be based on the anonymised data and that the anonymised EEG, tracking and questionnaire data will be permanently deposited on a publicly open database;
  - (f) If necessary any data from me will be referred to by a pseudonym in any publications arising from the research;
  - (g) I have been informed that a summary copy of the research findings will be forwarded to me, should I request this.

(Please tick) ☐ **yes** ☐ **no**

I wish to receive a copy of the summary report research findings. (Please tick) ☐ **yes** ☐ **no**

Participant signature:

Date:

Tony Steffert

Email:



### A3.4 Equipment and Consumables Datasheet

The 'Data Sheets' and 'Equipment Certificate' are on the accompanying DVD:

**List of documents:**

Steffert-Ethics-2015-5-Equipment-Mitsar-EEG202-DC

Steffert-Ethics-2015-5-Equipment-Mitsar-Quality-System-CE-Certificate

Steffert-Ethics-2015-5-Equipment-Mitsar-Quality-System-ISO\_13485

Steffert-Ethics-2015-6-Material Safety Data Sheet-Disposable Electrodes

Steffert-Ethics-2015-6-Material Safety Data Sheet-NuPrep Skin Prep Gel

Steffert-Ethics-2015-6-Material Safety Data Sheet-Skin Cleansing Swabs

Steffert-Ethics-2015-6-Material Safety Data Sheet-Ten-20 Electrode Gel

## A4 Questionnaire in Experiment 1, 2 and 3

### A4.1 NASA-TLX Questionnaire

#### NASA Task Load Index

Your ID:

Sonification ID:

##### 1. Mental Demand

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

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Low High

##### 2. Physical Demand

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

--	--	--	--	--	--	--	--	--	--

Low High

##### 3. Temporal Demand

How much time pressure did you feel due to the rate of pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

--	--	--	--	--	--	--	--	--	--

Low High

##### 4. Performance

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

--	--	--	--	--	--	--	--	--	--

Good Poor

##### 5. Effort

How hard did you have to work (mentally and physically) to accomplish your level of performance?

--	--	--	--	--	--	--	--	--	--

Low High

##### 6. Frustration

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

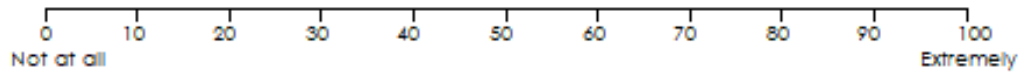
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Low High

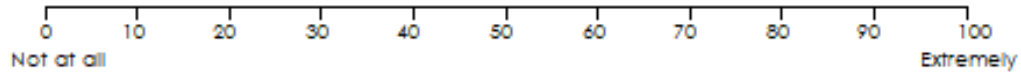
## A4.2 Emotional Rating Scales

Place a cross on each line to represent how you feel right now.

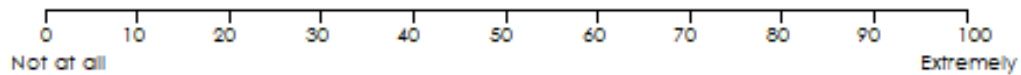
**Excited**



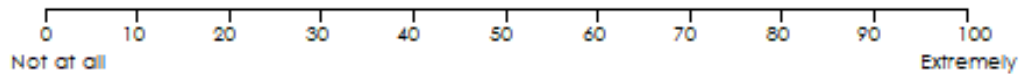
**Happy**



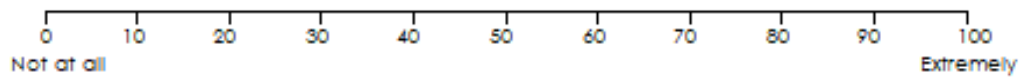
**Calm**



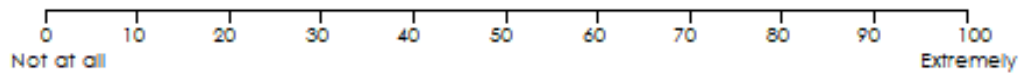
**Depressed**



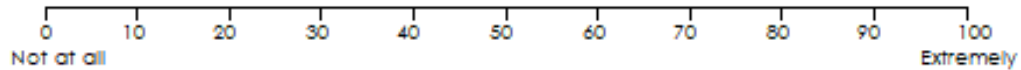
**Miserable**



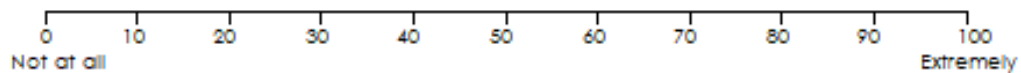
**Tense**



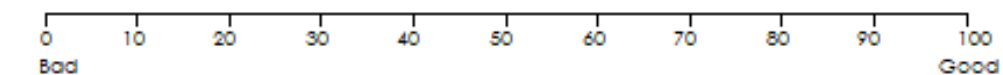
**Lethargic**



**Energetic**



**Overall mood**



### A4.3 AttrakDiff Questionnaire

The 28 word pairs of the AttrakDiff Questionnaire:

ID	AttrakDiff Low	AttrakDiff High
A#1	technical	human
A#2	complicated	Simple Yes
A#3	impractical	practical
A#4	cumbersome	straightforward
A#5	unpredictable	predictable
A#6	confusing	clearly structured
A#7	unruly	manageable
A#8	isolating	connective
A#9	unprofessional	professional
A#10	tacky	stylish
A#11	cheap	premium
A#12	alienating	integrating
A#13	separates me from people	brings me closer to people
A#14	unpresentable	presentable
A#15	conventional	inventive
A#16	unimaginative	creative
A#17	cautious	bold
A#18	conservative	innovative
A#19	dull	captivating
A#20	undemanding	challenging
A#21	ordinary	novel
A#22	unpleasant	pleasant
A#23	ugly	attractive
A#24	disagreeable	likeable
A#25	rejecting	inviting
A#26	bad	good
A#27	repelling	appealing
A#28	discouraging	motivating

### A3.4 Musical Training Questionnaire

#### **Musical Questions in experiment 1 and 2:**

This was administered in PsychoPy and participants had a choice of 7 boxes to tick.

**M1:** I engaged in regular, daily practice of a musical instrument (including voice i.e. Singing) for "X" or more years

**Answers:** 0, 1, 2, 3, 4-5, 6-9, 10

**M2:** At the peak of my interest, I practiced "X" or more hours per day on my primary instrument.

**Answers:** 0, 0.5, 1, 1.5, 2, 3-4, 5

**M3:** I have had "X" or more years of formal training on a musical instrument (including voice) during my lifetime.

**Answers:** 0, 0.5, 1, 2, 3-5, 6-9, 10

**M4:** I have had formal training in music theory for "X" or more years

**Answers:** 0, 0.5, 1, 2, 3, 4-6, 7

